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A Summary and Evaluation of Hanford Site Tank Farm Subsurface Contamination

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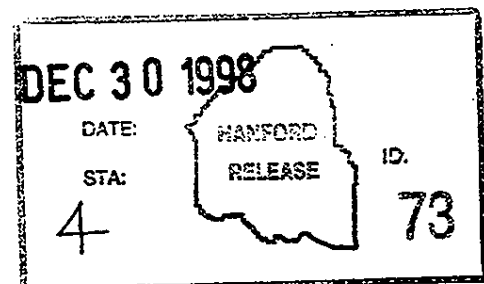
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Abstract: This document addresses the state of current knowledge in three critical areas: the geology of the 200 Areas, tank farm hydrology, and relevant geochemical processes. An overview of current SST waste inventories is presented and sources of tank wastes currently in the vadose zone are discussed. Groundwater monitoring data from the three Waste Management Areas (WMAs) under the *Resource Conservation and Recovery Act of 1976* (RCRA) assessment are discussed as is the very limited amount of data from analyses of soil samples contaminated with tank wastes. A preliminary conceptual model for the migration of tank wastes through the vadose zone is presented, along with an assessment of current data and analysis gaps.

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December 1998

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TERMS

ARHCO	Atlantic Richfield Hanford Company
CEC	cation exchange capacity
CLP	Contract Laboratory Program
DOE-GJO	U.S. Department of Energy, Grand Junction Office
DST	double-shell tanks
EPA	U.S. Environmental Protection Agency
GAO	General Accounting Office
HLAN	Hanford Site local area network
LANL	Los Alamos National Laboratory
NEPA	<i>National Environmental Policy Act of 1969</i>
PUREX	Plutonium-Uranium Extraction
RCRA	<i>Resource Conservation and Recovery Act of 1976</i>
REDOX	reduction-oxidation
SST	single-shell tanks
TBP	tributyl phosphate
TOC	total organic carbon
TWINS	Tank Waste Information Network System
TWRS	Tank Waste Remediation System
WSTRS	<i>Waste Status and Transaction Record Summary</i>

A SUMMARY AND EVALUATION OF HANFORD SITE TANK FARM SUBSURFACE CONTAMINATION

1.0 BACKGROUND AND SCOPE

Tank Waste Remediation System (TWRS) cleanup decisions require an understanding of vadose zone conditions and processes. TWRS cleanup decisions also depend on sitewide perspectives on groundwater movement, total contaminant burden, and performance criteria.

This document summarizes the relevant technical knowledge and understanding of a team of five Hanford scientists about subsurface conditions and processes that are important to TWRS cleanup decisions. This document was not developed to address any specific regulatory requirements, nor was any attempt made to cite regulatory requirements for actions that are assumed to happen in the future.

Specifically, this document addresses the state of current knowledge in three critical areas: the geology of the 200 Areas (Section 2.1 and Appendix A), tank farm hydrology (Section 2.2 and Appendix B), and relevant geochemical processes (Section 2.3 and Appendix C). An overview of current SST waste inventories is presented in Section 3.1 and sources of tank wastes currently in the vadose zone are discussed in Section 3.2. Gamma-ray logging data are discussed in Section 3.3. Groundwater monitoring data from the three Waste Management Areas (WMAs) under the *Resource Conservation and Recovery Act of 1976* (RCRA) assessment are discussed in Section 3.4. The very limited amount of data from analyses of soil samples contaminated with tank wastes is discussed in Section 3.5. A preliminary conceptual model for the migration of tank wastes through the vadose zone based on the information and data presented in Chapters 2 and 3 is presented in Chapter 4. Based on information presented in Chapters 2 through 4, an assessment of current data and analysis gaps is presented in Chapter 5. A "path forward" is discussed in Chapter 6.

Our current conceptual understanding of impacts of unplanned releases of tank wastes into the vadose zone discussed in Chapter 4 is considered an initial model from which more detailed conceptual models would be developed during site-specific planning activities. Site-specific conceptual models addressing migration of tank waste through the vadose zone will undoubtedly include detailed tank farm or even tank-specific information to best focus characterization plans.

This document identifies references for the relevant data and, where possible, summarizes that data. As noted, it also identifies data needs that will be important to understanding vadose zone conditions and processes. This includes proposing preliminary descriptions of conditions and processes that control migration of contaminants from unplanned releases of tank waste into the vadose zone based on newly obtained data.

This document is designed to be updated periodically to reflect new information and improved understanding that results from additional vadose zone characterization. Currently,

This document is designed to be updated periodically to reflect new information and improved understanding that results from additional vadose zone characterization. Currently, our knowledge of vadose zone conditions and processes is limited. However, understanding where specific data gaps exist helps to focus planning for data collection activities.

2.0 SUMMARY OF HANFORD SITE NATURAL SYSTEM DESCRIPTIONS

2.1 GEOLOGY AND STRATIGRAPHY

The geology of the soil and rock layers underlying the 200 Areas of the Hanford Site has been examined extensively. The current level of understanding is documented in Appendix A. Based on the geologic data sets and unit descriptions contained in Appendix A, four conceptual geologic models have been prepared for Hanford Site SST farms. These models apply, one each, to the north and south halves of the 200 West and 200 East Areas.

The main vadose zone stratigraphic units at Hanford Site SST farms are backfill; Hanford formation units H1, H1A, H2, H2A, and H3; the Plio-Pleistocene unit; and the Ringold Formation members of Wooded Island and Taylor Flat. These units provide the basic framework within which SST farm vadose zone geologic conditions can be interpreted.

The 200 West Area north model consists of the following formation units, in descending order:

- Backfill (compacted materials from original excavation [H1 and H2])
- Coarser segments of Hanford formation units H1 and H3. Intercalated strata of the sand-dominated facies occur locally in both units.
- Sand-dominated facies of H2
- At some locations, unit H2 coarsens downwards into unit H3. Where this occurs, the transitional interval is designated unit H2A.
- Plio-Pleistocene unit
- Ringold Formation, unit E.

The 200 West Area south model consists of the following formation units, in descending order:

- Backfill (compacted materials from original excavation [H1 and H2])
- Coarser segments of Hanford formation units H1 and H3. Intercalated strata of the sand-dominated facies occur locally in both units.
- Silt-dominated facies of H2
- At some locations, unit H2 coarsens downward into unit H3. Where this occurs, the transitional interval is designated unit H2A.

- Plio-Pleistocene unit
- Ringold Formation, unit E.

The 200 East Area north model consists of the following formation units, in descending order:

- Backfill (compacted materials from original excavation [H1 and H2])
- Coarser segments of Hanford formation units H1 and H3. Intercalated strata of the sand-dominated facies occur locally in both units. Units thin and fine to the south.

The 200 East Area south model consists of the following formation units, in descending order:

- Backfill (compacted materials from original excavation [H1 and H2])
- Coarser segments of Hanford formation units H1 and H3. Intercalated strata of the sand-dominated facies occur locally in both units. Units thin and fine to the south.
- Where Ringold Formation strata is found in the vadose zone beneath 200 East Area SST farms, unit A and the lower mud unit of the member of Wooded Island also are present.

Clastic dikes are inferred to be present beneath all the SST farms. In some locations, they may cross cut the Plio-Pleistocene (Singleton and Lindsey 1994).

2.2 TANK FARM HYDROLOGY

Tank leaks occur under variably saturated conditions, making natural recharge from meteoric water (from winter precipitation and snowmelt), artificial recharge from operations-related sources, and vadose zone hydrology important long-term drivers for contaminant movement to groundwater.

Tank farm surfaces are covered with gravel to prevent vegetation growth and provide radiation shielding for site workers. Bare gravel surfaces, however, enhance net infiltration of meteoric water. Infiltration is further enhanced in tank farms by the effect of percolating water being diverted by an impermeable, sloping surface. This umbrella effect is created by the 23 m diameter buried tank domes. Water, shed from the tank domes, flows down the tank walls into underlying sediments. Sediments adjacent to the tanks, while remaining unsaturated, can attain elevated moisture contents. In addition, other sources of recharge include unintentional surface spills, infiltration of surface runoff from leaking water lines, and ancillary tank-related equipment. Enhanced infiltration from a gravel-covered tank dome,

spills, and water-line leaks can mobilize a tank leak and provide potential for faster transport to the water table.

In general, two types of moisture movement can occur in the tank farm vadose zone: piston flow and preferential flow. Piston flow (wetting-front infiltration) refers to uniform moisture movement through the soil matrix whereby infiltrated water displaces initial water (NRC 1995). Under piston-like flow conditions most, if not all, preexisting water ("old" water) is displaced and moved ahead of the "new" infiltration water added from above (NRC 1995). Preferential flow is the process whereby water and contaminants move along preferential pathways. Preferential pathways can be natural (e.g., clastic dikes) or constructed (e.g., migration down the casing of unsealed monitoring wells). Other potential preferential pathways during tank leaks include wetting-front instability or "fingering" flow. Wetting-front instability, reported in petroleum-related literature, is a special case of interface instability during immiscible fluid displacement in porous media. The phenomenon is triggered by unfavorable differences between the viscosities and densities of two fluids across their interface, a condition that can potentially exist during tank leaks. Tank farm hydrology is covered in more detail in Appendix B.

A field study (Sisson and Lu 1984) in the 200 East Area south of the Plutonium-Uranium Extraction (PUREX) Plant demonstrated the effect of geologic heterogeneities on water contents in a natural arid setting. The higher observed water content values were strongly correlated with fine soil layers, which have a higher water holding capacity than coarse soils. In addition, the observed profiles were remarkably similar for the 15-year interval between measurements at the field site (Fayer et al. 1995). This suggests that, in the absence of artificial recharge, the "natural" moisture contents of the sediments are essentially determined by the nature of geologic heterogeneity, and the vadose zone water content profiles are at quasi-equilibrium with the natural recharge rate. This is also demonstrated by the moisture content profiles in borehole 299-W10-196 near tank 241-T-106 in the 200 West Area; the data collected in 1993 show a much higher moisture content in the fine-grained Plio-Pleistocene and upper Ringold layers than in the Hanford formation (Freeman-Pollard et al. 1994).

The dominance of lateral movement is a unique feature of unsaturated flow that is enhanced in an arid setting. Horizontal stratification enhances such movements, because, at high tension (i.e., in dry soil), hydraulic conductivities of fine-textured materials are relatively high and the fluid prefers to spread laterally in the fine media than to move vertically through the coarse media. Such a phenomenon is referred to as moisture-dependent anisotropy, and can potentially be a dominant "funneled" flow mechanism for situations where a fine layer overlies a coarse layer along an inclined bed. This has important implications for vadose zone contaminant transport of fluid from tank leaks. For example, measurements of vadose zone contamination, using gamma radiation logs in wells around the tank T-106 leak, suggest significant lateral movement of waste in the sediment layers (Routson et al. 1979).

Geologic heterogeneities, as well as soil hydraulic properties (i.e., moisture content versus matric potential and unsaturated hydraulic conductivity versus moisture content relationships), must be known to evaluate the storage and flow properties of tank farm soils.

Furthermore, assessing the ability of the vadose zone to act as a buffer requires properly accounting for conditions under which the tank leak chemistry itself may affect soil hydraulic properties and the mobility of contaminants. For the undisturbed natural conditions, Khaleel and Freeman (1995) compiled available data on hydraulic properties for the principal formations and soil types in the 200 Areas plateau. However, the database needs to be updated and its applicability to tank farm soils evaluated.

In summary, leaks from tanks and tank-related sources are expected to move downward by advection; the layered nature of the sediments would cause some lateral spreading. A secondary mode of transport is through preferential flow. Preferential flow can be via clastic dikes and in the form of fingering, funnel flow, and flow along the unsealed annular spaces around drywells. Also, the characteristics of past tank liquids (e.g., high pH, high sodium concentration, and high temperature) could result in chemically enhanced mobility of some contaminants.

As described in Johnson and Chou (1998) and in Section 3.5, groundwater flow and contaminant distribution in groundwater must be understood to distinguish between the contributions of intentional liquid discharges to cribs, trenches, etc., and unplanned releases of tank waste to the contaminant concentrations in groundwater. Appendix B summarizes current flow conditions and contaminant distributions in groundwater beneath the 200 Areas, including the tank farms.

2.3 GEOCHEMISTRY SUMMARY

This section covers geochemical factors and material properties of the sediment and the soil column that control contaminant transport in the vadose zone or that might be useful in determining contaminant sources or supporting waste retrieval decisions based on leak detection. Contaminant transport is influenced by both hydraulic properties of vadose zone lithologic units and chemical reactivity of sediment minerals with water and waste solutions.

2.3.1 Initial Conditions and Baseline Parameters

The particle size distribution in lithologic units partially controls the hydrologic properties and, indirectly, the chemical reactivity. Coarse-grained materials, dominated by cobbles, pebbles, and coarse sand, have a higher hydraulic conductivity and lower chemical reactivity than fine sands, silts, and clay-size ($<2\ \mu\text{m}$) materials. The fine materials account for most of the lateral dispersion of fluids, chemical sorption of contaminants, and other chemical reactivity with waste solutions.

Hydraulic properties can be altered by secondary chemical precipitates, such as calcium carbonate, that can act as a particle cementing agent. A general measure of chemical reactivity is the sodium cation exchange capacity (CEC). Particle size distributions, calcium carbonate cement, and sodium CEC have been determined on vadose zone samples from several lithologic units and are discussed in more detail in Appendix A. In general, the

Hanford formation is dominated by medium and coarse sands and gravels; the Plio-Pleistocene layer by fine sands, silts, and clays; and the Ringold Formation is variable. The upper and lower Ringold tend to be fine grained; the middle Ringold is coarser. Calcium carbonate cement is generally less than 3 percent in the Hanford formation, but is generally up to 7 percent in the Plio-Pleistocene and can be more than 30 percent locally. The upper Ringold also can have considerable calcium carbonate cement (more than 20 percent locally). CEC values are generally 5 to 6.5 meq of sodium/100 g of sediment and may be up to 7 to 8 meq/100 g in fine-grained materials.

2.3.2 Background Mineralogical and Chemical Characteristics

Mineralogical characterization of vadose zone sediments has not been conducted as extensively as particle size distribution and sorption properties. The mineral content of particles larger than 2 mm, which include coarse sand, gravels, and cobbles is dominated by quartz, feldspars, and rock fragments. The sand-size-and-smaller fraction (<2 mm plus clays) contains 60 to 80 percent quartz and feldspars with up to 10 percent mica and secondary iron-bearing minerals. The clay-size fraction (<2 μm) consists mostly of smectite-type clays and mica/illites with smaller amounts of chlorite, vermiculite, and kaolinite along with hydrous oxides. The clay-size fraction generally makes up less than 20 wt percent of the <2 mm fraction. Higher clay contents can influence sorption properties of sediments disproportionate to the clay volume. Together, clays and hydrous oxides account for most of the sorption capacity and selectivity for waste contaminants.

Background chemical composition, including major and trace constituents, radiochemical content, and organic content of soils, provides a baseline for determining contaminant levels and evaluating risks associated with retrieval options. Sitewide soil background chemical and radiochemical composition have been reported. Specific tank farm background levels have not been determined, but are not expected to differ significantly from Sitewide estimates. Some organic carbon values also are available. These data and references are summarized in Appendix C.

2.3.3 Chemical Mechanisms Controlling Contaminant Transport

Dissolved and suspended contaminants in waste fluids infiltrating through sediments are transported by advection or diffusion or dispersion mechanisms. Several sediment-water chemical mechanisms control the dissolved concentration and relative mobility of contaminants. These include solubility-precipitation, ionic diffusion, particulate (including colloids) formation, and complexation, ion exchange, and sorption. The dominant mechanisms used to estimate and model transport are solubility, precipitation, and sorption. (Sorption is a composite of several mechanisms and a measure of total contaminant distribution between the liquid and solid phases.) Over the last 40 years, a number of reviews of the literature have been conducted. The reviews have emphasized soil chemistry, focusing on sorption and related processes that influence the contaminant-retention capacity of

sediments and retardation factors. Appendix C covers these mechanisms and reviews in more detail.

Solubility and sorption behavior are controlled by a number of parameters. One is the pH of solutions in contact with soil minerals. Related parameters are electrical conductivity (a measure of dissolved solids) and E_h , a measure of oxidation-reduction potential. In general, the natural buffering capacity of mineral-water interactions in Hanford Site groundwater systems results in pH ranges of 7.5 to 8.5. Soil pH values, obtained by reacting small amounts of soil and water in 1:1 ratios yield values of about 7.7 to 8.8. Specific conductance values for uncontaminated groundwater are about 200 to 300 S/cm (Siemens/centimeter) compared with Columbia River water of about 140 S/cm. For comparison, specific conductances of contaminated groundwater in the T-TX-TY tank farms were above 2000 S/cm. Groundwater E_h values range from about 280 to 380 mv at pH values near 8, which indicates that the groundwater is moderately oxidizing. Vadose zone conditions would be expected to be more oxidizing because pore volumes are partially filled with air. Locally, the presence of minerals such as pyrite (iron sulfide) or concentrations of organic constituents may cause reducing conditions in the vadose zone.

Various inorganic and organic complexants, colloids, and particulates can potentially interact with contaminants of concern and affect their mobility in the soil column. Some complexants are clearly present in the Hanford soil-water environment. Their interactions with contaminants are known and reflected in sorption values used in contaminant migration models. For example, aqueous carbonate species are ubiquitous in Hanford vadose zone waters and react with soluble uranium to form mobile aqueous species. Other complexants, such as organics that have been introduced into tank waste, may have influenced contaminant mobility in the vadose zone, but these species have not been clearly identified in the vadose zone. Similarly, the formation of colloids and particulates that could carry contaminants in migrating fluids are postulated, but not clearly identified as present or functional in the vadose zone.

2.3.4 Sorption and Related Contaminant Retardation Processes

Sorption is a generic term describing the ratio of the amount of contaminant associated with a gram of solid phase (sediment or mineral) divided by the amount dissolved per milliliter of solution. It consequently has units of milliliters per gram and is usually expressed as K_d . The K_d is not a true thermodynamic ion exchange constant because multiple mechanisms occur that control the partitioning of contaminants between the liquid and solid phases. The sorption process generally is considered the most important measurable contaminant-retardation process for vadose zone mobility, and has been investigated since the early 1950's as the basis for crib disposal capacity and trench field capacity. The K_d is related to contaminant retardation factors (R_d) in porous media by functions such as

$$R_d = 1 + (\rho_b/\phi_e)K_d$$

where ρ_b is the porous media bulk density and ϕ_e is the effective porosity or moisture content in the unsaturated media. K_d values are affected by competing cations, ionic strength of solutions, pH, mineralogy, complexants, and redox (E_h). Consequently, they are somewhat site specific. K_d values and ranges for a number of elements are given in several references in Appendix C. The overall capacity of soils and sediments to sorb ions is often expressed as the sodium CEC and provides a preliminary measure of the ability of soils to retain leaked contaminants before breakthrough occurs. The CEC does not provide information on cation selectivity or reversibility. Certain minerals and sorption sites selectively sorb specific cations (for example cesium on certain mica sites). The sorption-desorption kinetics (reversibility) measures the sediment's ability to resist elution and can lead to variable amounts of hysteresis between forward and reverse reactions. This may be an important factor when multiple contaminant releases take place at the same site.

2.3.5 Geochemical Behavior of Key Contaminants in Tank Leak Fluids

Only a relatively small number of the many radionuclides and chemicals present in the tank waste are potential long-term environmental contaminants of real concern because they are present in sufficient quantity, are sufficiently long-lived (in the case of radionuclides), and are rather mobile. Prominent radionuclides with these characteristics that are identified in contaminated vadose zones include ^{99}Tc , ^{14}C , ^{237}Np , and uranium, plutonium, and americium isotopes. Nitrate is the chemical species identified in notable quantities. Relatively short-lived radionuclides ^{60}Co , ^{137}Cs , and ^{90}Sr also are discussed for completeness.

These constituents are expected to exhibit varying degrees of mobility in the vadose zone. Laboratory and field evidence supports this expectation. As a general rule, elements that tend to form anionic and neutral aqueous species are the most mobile because little or no interaction with solid phases occurs. Those that form cationic species tend to react with solid phases and be pulled out of solution during migration through the soil column. The behavior of elements also can change noticeably with changes in environmental conditions. This should be evaluated in tank leak contaminated zones because of the significant differences in the chemistries of the soil-water system and some tank liquids. More laboratory data are available for contaminant behavior in undisturbed Hanford soil than for tank fluid chemistry. Primary information sources include Serne and Wood (1990), Kaplan and Serne (1995), and Kaplan et al. (1995). The following paragraphs briefly summarize what is and is not known about these constituents.

Technetium-99 and Nitrate. Technetium-99 and nitrate have routinely been shown to be essentially nonreactive in the vadose zone, both under undisturbed conditions and when affected by tank fluid. Both are assumed to exist as anionic species under either condition. Technetium-99 can be immobilized in highly reducing environments, but the soil column at the Hanford Site is too oxidizing. At best, local reducing conditions might occur temporarily.

Carbon-14. Carbon-14 mobility is complex because of the many reactions in which it can be involved as either a gas, a liquid, or a solid. Frequently, to be conservative, ^{14}C is modeled as completely mobile ($K_d = 0$ mL/g) because aqueous species are anionic. The large ^{14}C spike in

the analyzed soil column near the tank bottom in the tank T-106 leak is interesting because of the apparent significant retardation in ^{14}C migration demonstrated by the field data. What reactions contributed to this spike or whether some aspect of tank fluid chemistry enhanced the retardation effect is unclear.

Uranium. Uranium solubility is very sensitive to pH changes. Because temporary pH increases will occur locally in the vadose zone following tank leaks, uranium mobility may increase or decrease compared to its mobility in undisturbed soil. However, the effects are temporary and the buffering capacity of the soil-water system will return local pH values to ambient (about pH = 8). Soluble uranium readily forms anionic species in undisturbed conditions and is very mobile. Tank chemistry characteristics probably cannot enhance the mobility of dissolved uranium.

Transuranic Elements. Of the three transuranic elements identified in the vadose zone, americium, plutonium, and neptunium, empirical sorption tests show that americium and plutonium are highly sorbing and neptunium is moderately sorbing. These radionuclides are expected to migrate over thousands of years through the vadose zone under undisturbed conditions. Tank fluid characteristics may, at least temporarily, enhance transuranic isotope mobility by introducing organic complexants or facilitating the formation of colloids or other particulates that could carry these isotopes with migrating fluid. To date no evidence has been found that demonstrates the existence or effectiveness of such mobilizing phenomena in Hanford Site soils. However, the tank T-106 data imply that some mobilization of americium and plutonium isotopes has occurred, at least temporarily. Further evaluation of these radionuclides is recommended to determine the current state of their mobility.

Cesium-137. Cesium-137 normally is very reactive and unlikely to migrate appreciably in undisturbed Hanford Site soil. However, enhanced mobility has occurred in some tank-leak-contaminated zones. A prime contributor to enhanced mobility is expected to be competition for sorption sites in soil phases between ^{137}Cs and the extremely high concentrations of sodium also present in leaking tank fluids. If so, such mobility is temporary; the buffering action of the normal soil-water system gradually reduces the amount of sodium in solution. Consequently, ^{137}Cs mobility will greatly decrease over time. This, combined with a relatively short half life, will prevent ^{137}Cs from becoming a potential long-term groundwater contaminant.

Strontium-90 and Cobalt-60. Strontium-90 and ^{60}Co are moderately sorbing under undisturbed conditions. Organic complexing agents in some tank fluids may enhance ^{90}Sr and ^{60}Co mobility. Strontium-90 mobility also may be enhanced because it competes for sorption sites with increased calcium in leaking tank fluid. Organic species likely are unstable over long periods, thereby limiting the time over which enhanced mobility is effective. The stability and continued ability of organic complexants to enhance the mobility of these nuclides would be of interest if their half lives were longer. Similarly, elevated calcium levels will return to ambient over time as the buffering action of soil-water reactions occurs.

3.0 DATA

This chapter provides an overview of currently available data that support the development of a conceptual understanding of vadose zone processes. Much of the information presented in this chapter comes from documents dating from the 1950's, '60's, and '70's. The work reported in these documents predates our current "Quality Assurance" pedigree for procedures, plans, projects, and programs, and computerized instrumentation. Nevertheless, the measurement technologies used in the studies were state of the art at the time. More importantly, these historical records provide the only opportunity for reconstructing activities that could have affected or did affect the vadose zone.

3.1 CURRENT TANK WASTE INVENTORIES

3.1.1 Genesis of Hanford Site Tank Waste

From 1943 through 1964, 149 single-shell tanks (SSTs) were constructed to store liquid waste generated from plutonium production and separation operations at the Hanford Site. Many neutralized nitric acid-based waste types were generated from several operations, including the bismuth phosphate process (T Plant and B Plant), the uranium recovery process, the reduction-oxidation (REDOX) process, the PUREX process, and several isotope recovery processes (Anderson 1980, Agnew 1997). In addition, a number of waste streams from the 100 and 300 Areas also were added to the SSTs. Managing the large volumes of liquid waste generated in the processing facilities proved to be a challenging task.

As part of the liquid radioactive waste management program, large volumes of tank waste supernatant liquid were discharged to the soil column (Waite 1991). Frequently, three or four SSTs were interconnected so that liquid waste could cascade from one tank to the next with the liquid effluent from the last tank in a cascade being transferred to cribs. A number of evaporator facilities were constructed to support objectives to reduce the liquid waste volume. Liquid waste was collected in a feeder tank (i.e., a designated SST), then pumped to the evaporator facility. After the volume was reduced significantly, the material was returned to an SST to allow the solids (currently called saltcake) to form and settle out. The supernatant liquid would then be recycled to the evaporator to be further concentrated. Long-term operations of the various evaporator facilities have led to extensive commingling of waste streams. In addition, several in-tank solidification programs were used to reduce waste volumes. Heaters were placed in some tanks in the BY tank farm to evaporate liquids. Supernatant liquid was moved around the tanks within this farm to support the in-tank solidification program. A second approach involved allowing high-level waste to boil in selected tanks in the A, S, and SX tank farms, which led to self-concentration.

The practice of adding waste to SSTs ended in 1980 and a program began to transfer all pumpable liquids from the SSTs to the newer double-shell tanks (DSTs). The waste currently remaining in the SSTs consists primarily of sludge, saltcake, and interstitial liquid (Hanlon 1998).

3.1.2 Current Hanford Tank Waste Inventories

Because of the extensive transfer and commingling of waste types over the more than 50 years of SST operations, the chemical and radioactive waste inventory currently in each SST is uncertain. Over the last decade, two approaches have been used to estimate the Hanford Site tank waste inventories.

The first was an SST waste characterization program that began in 1989 (Winters et al. 1989). A selected number of cores were collected from the tank of interest and transferred to the analytical laboratory for extensive characterization. Tank inventories were estimated based on laboratory analytical results and documented in tank characterization reports. Currently, the available database from sampling and analysis is somewhat limited. Tank characterization reports and tank waste analysis data are available electronically on the Tank Waste Information Network System (TWINS) database.

The second approach, pioneered by Francis Jungfleisch (Jungfleisch 1984) and brought to fruition by Steve Agnew and coworkers at the Los Alamos National Laboratory (LANL), involved estimating tank waste inventories based on process records and waste transfer documentation. Waste transfer data are summarized in the *Waste Status and Transaction Record Summary* (WSTRS), Rev. 2 (Agnew et al. 1995); inventory estimates are reported for each tank in the *Hanford Tank Chemical and Radionuclide Inventories: HDW Model*, Rev. 4 (Agnew 1997).

Results from both the laboratory analyses and the HDW Model were evaluated and a best basis inventory estimate was developed for each SST and DST on the Hanford Site (Kupfer et al. 1997). The best basis inventory estimate was published individually for each tank. Best basis inventory values are available electronically through the TWINS database.

3.1.3 Tank Inventories at the Time of Leaks

Future modeling efforts to evaluate the long-term impacts of any tank leak will require an inventory estimate of chemicals and radionuclides lost to the vadose zone at the time of the leak. One approach for estimating tank leak inventories is using the HDW model to predict tank compositions during the time the tank was thought to have leaked. Such information could then be coupled with the estimated leak volume to calculate the tank waste inventory lost during a leak event. Agnew and Corbin (1998) constructed the tank waste inventories believed to have been present when the tanks were thought to have leaked while developing his historical leak model. Basically, the HDW model was run to specific points in time to predict the chemical and radionuclide inventories for four tanks (SX-108, -109, -111, and -112). The modified HDW model will be used to develop inventory estimates for the periods other tanks are thought to have leaked.

3.2 SOURCES OF TANK WASTE CURRENTLY IN THE VADOSE ZONE

During the operating lifetime of the chemical separations processes at the Hanford Site, high-level radioactive liquid waste entered the vadose zone—both intentionally and inadvertently—through several pathways. These included tank waste intentionally discharged to the vadose zone, waste transfer line leaks, and leaks associated with SST waste storage and operations.

3.2.1 Tank Waste Intentionally Discharged to the Vadose Zone

From 1944 to 1966, approximately 458 035 kL (121,000,000 gal) of tank waste liquid were intentionally discharged from SSTs to the soil column (Waite 1991). This waste was discharged to cribs, injection wells, and specific retention trenches located near the tanks of origin. The types of liquid waste discharged included: first- and second-cycle waste coming from the bismuth phosphate processes, 224 waste from plutonium purification, and, in limited amounts, evaporator bottoms from 242-T and 242-B Evaporators and scavenged first cycle supernatant liquid. The specific dates, origins, volumes, and disposal sites for each of these waste types are reported in Waite (1991) and shown in Tables 3-1 and 3-2. Over the same period, billions of gallons of slightly contaminated water from various processing facilities also were discharged to ponds, trenches, ditches, and cribs in and around the 200 Areas.

Although evaluating potential impacts to the vadose zone from intentional discharge of tank waste supernatant liquid is outside the scope of the TWRS Vadose Zone Program, such discharges may have affected the vadose zone under some tank farms. The total inventory of radionuclides and contaminants discharged into the vadose zone from these sources has not been fully evaluated or compared to the potential inventory from discharges caused by tank leaks.

Table 3-1. Fuel Reprocessing Waste Intentionally Discharged to the Ground from Single-Shell Tanks.

	Years discharged	Disposal sites	Total volume discharged (L [gal])	Total curies (decayed to December 1989)
Second-cycle supernatant from B Plant and T Plant ¹	1948-1956	216-B-7A crib 216 B-7B crib	222,280,000 [58,725,000]	5,618
Cell drainage from B Plant and T Plant ¹	1951-1956	216 B-8 crib 216-T-5 trench 216-T-19 crib		
Plutonium concentration and decontamination from 2224-T and 224-B facilities ¹	1946-1956	216-T-32 crib		
First cycle supernatant waste from B Plant and T Plant	1953-1954	BX trenches (35, 36, 38-41) T trenches (14-17) TX trenches (21-24)	17,835, 000 [4,711,000]	11,665

Table 3-1. Fuel Reprocessing Waste Intentionally Discharged to the Ground from Single-Shell Tanks.

	Years discharged	Disposal sites	Total volume discharged (L [gal])	Total curies (decayed to December 1989)
Evaporator bottoms from 242-T and 242-B Evaporators	1954	216-B-37 trench 216-T-25 trench	7,320,000 [1,934,000]	10,155
Scavenged first cycle supernatant liquid from T Plant	1955-1956	216-T-26 crib	12,000,000 [3,170,000]	717
Total			259,435,000 [68,540,000]	28,155 ²

Notes: Numbers reflect data in the database and were used so they could be traced. They reflect greater accuracy than warranted by the number of figures shown. Two or three significant figures would better reflect data accuracy.

From: Waite, J. L., 1991, *Tank Wastes Discharged Directly to the Soil at the Hanford Site*, WHC-MR-0227, Westinghouse Hanford Company, Richland, Washington.

¹Volume and radionuclide content have been combined because waste was sent to common disposal sites.

²Inventory does not include tritium, ⁹⁹Tc, or ¹²⁹I.

Table 3-2. Uranium Recovery Tank Waste Intentionally Discharged to the Ground.

Disposal site	Years Discharged	Total volume discharged (L [gal])	Total curies (decayed to December 1989)
216-T-18 (test run)	1953	1,000,000 [264,000]	223
BY cribs (7 cribs)	1954-1955	33,840,000 [8,940,000]	14,270
216-B-42 (BX trench)	1955	1,500,000 [396,000]	1,010
BC cribs (6 cribs)	1956-1957	38,960,000 [10,293,000]	3,246
BC trenches (15 trenches)	1956-1958	79,690,000 [21,053,000]	11,587
Total		154,990,000 [40,946,000]	30,336 ¹

Notes: Numbers reflect data in the database and were used so they could be traced. They reflect greater accuracy than warranted by the number of figures shown. Two or three significant figures would better reflect data accuracy.

From: Waite, J. L., 1991, *Tank Wastes Discharged Directly to the Soil at the Hanford Site*, WHC-MR-0227, Westinghouse Hanford Company, Richland, Washington.

¹Inventory does not include tritium, ⁹⁹Tc, or ¹²⁹I.

3.2.2 Waste Transfer Line Leaks

Approximately 70 unplanned releases and spills associated with tank waste are identified in the Waste Information Data System (WIDS) (Waite 1991 and Maxfield 1979). Waite (1991) estimated that more than 379 kL (100,000 gal) of liquid waste have been released to the ground from the transfer line leaks. Presumably, many of these leaks were inside the tank farms and are within the scope of the TWRS Vadose Zone Program.

For example, Figures 3-1 and 3-2 identify unplanned releases in and around the S/SX tank farm complex. Radioactive materials from the unplanned releases in this area undoubtedly account for some of the near-surface contamination identified in gamma logging activities. Thus, as with the intentional tank waste discharges discussed earlier, transfer line leaks in or near tank farms may have affected the vadose zone under the tank farms.

3.2.3 Leaks Associated with Single-Shell Tank Waste Storage and Operations

Currently, 67 SSTs are listed in the monthly Waste Tank Summary Report¹ (Hanlon 1998) as "confirmed or assumed" leakers. Along with the list of confirmed or assumed leaking tanks, this document provides estimated leak volumes, the date a tank was declared a leaker, and references. However, the leak dates listed in Hanlon are the dates the tank was declared or assumed a leaker, not the time the leak was first suspected. In addition, uncertainties exist in the estimated tank leak volumes and even in the selection of tanks included in this list. This section is intended to address the complexities that have contributed to these uncertainties. In the context of this discussion, tank leaks are defined as any incident where high-level radioactive waste enters the soil column from tanks or transfers between tanks within a farm.

The two approaches used for detecting leaks from SSTs were in-tank waste level measurements and gamma-ray logging in monitoring wells around and, in two tank farms, under the tanks (Welty 1988). Neither approach provided unequivocal evidence of a tank leak in all cases. In-tank waste level measurements become less certain when solid waste surfaces are encountered. When liquids are removed from tanks with a solid surface, the surface becomes irregular. Under these conditions, estimating waste volumes from spatially limited surface-level measurements become uncertain (Swaney 1983).

¹The monthly *Waste Tank Summary Report* is the official DOE inventory for radioactive waste stored in underground storage tanks in the 200 Areas of the Hanford Site. The data depicting the status of stored radioactive waste and tank integrity are reported in this document. This document is updated monthly to reflect the most current referenceable data source. The statuses currently listed in the Waste Tank Summary Report are updated as new information becomes available. Therefore, the information listed in the monthly *Waste Tank Summary Report* is taken as the starting point for any discussion of Hanford Site tank leaks.)

Figure 3-1. Unplanned Releases in and Around the S/SX Tank Farm Complex (ICF KH 1996).

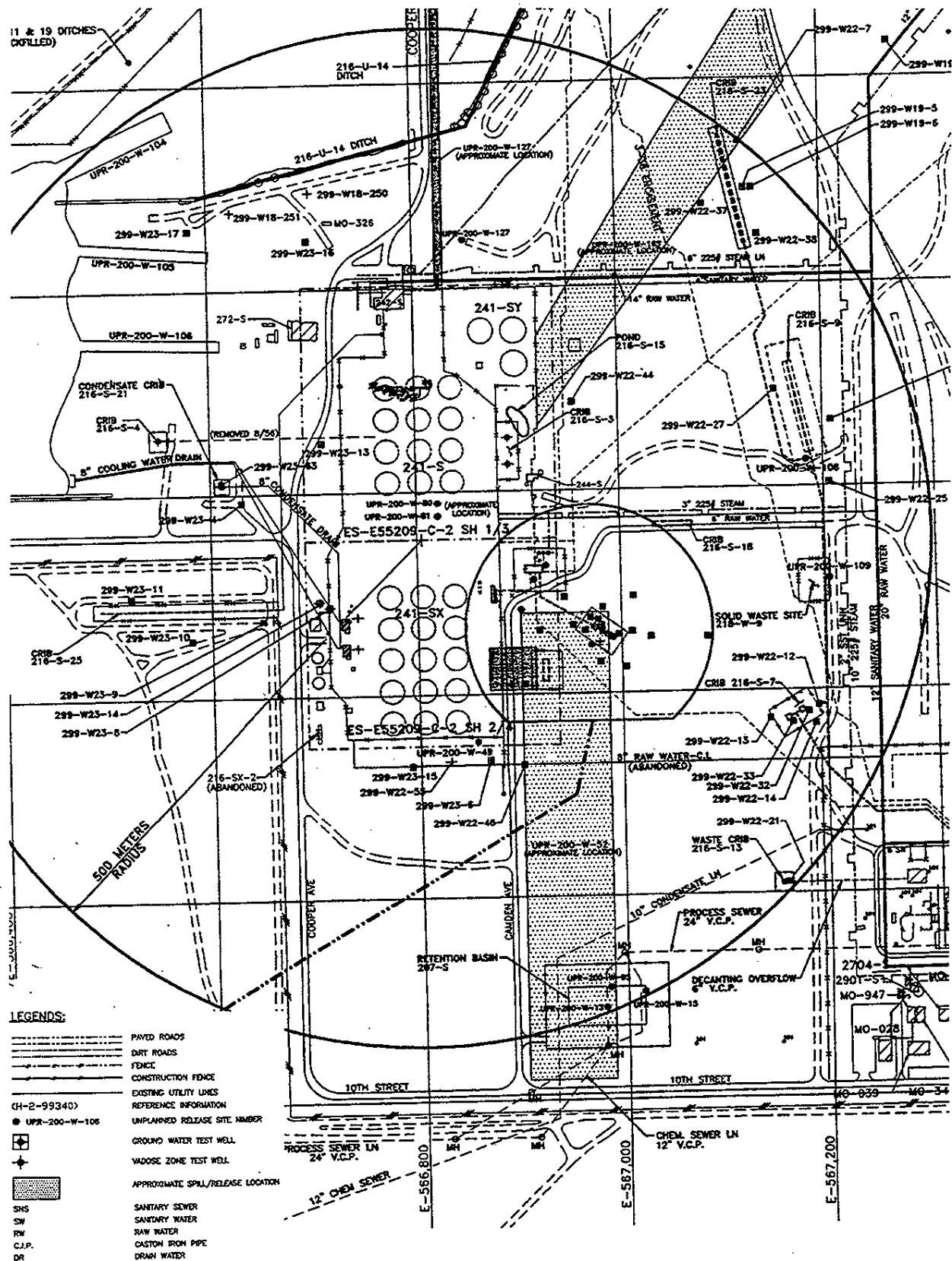
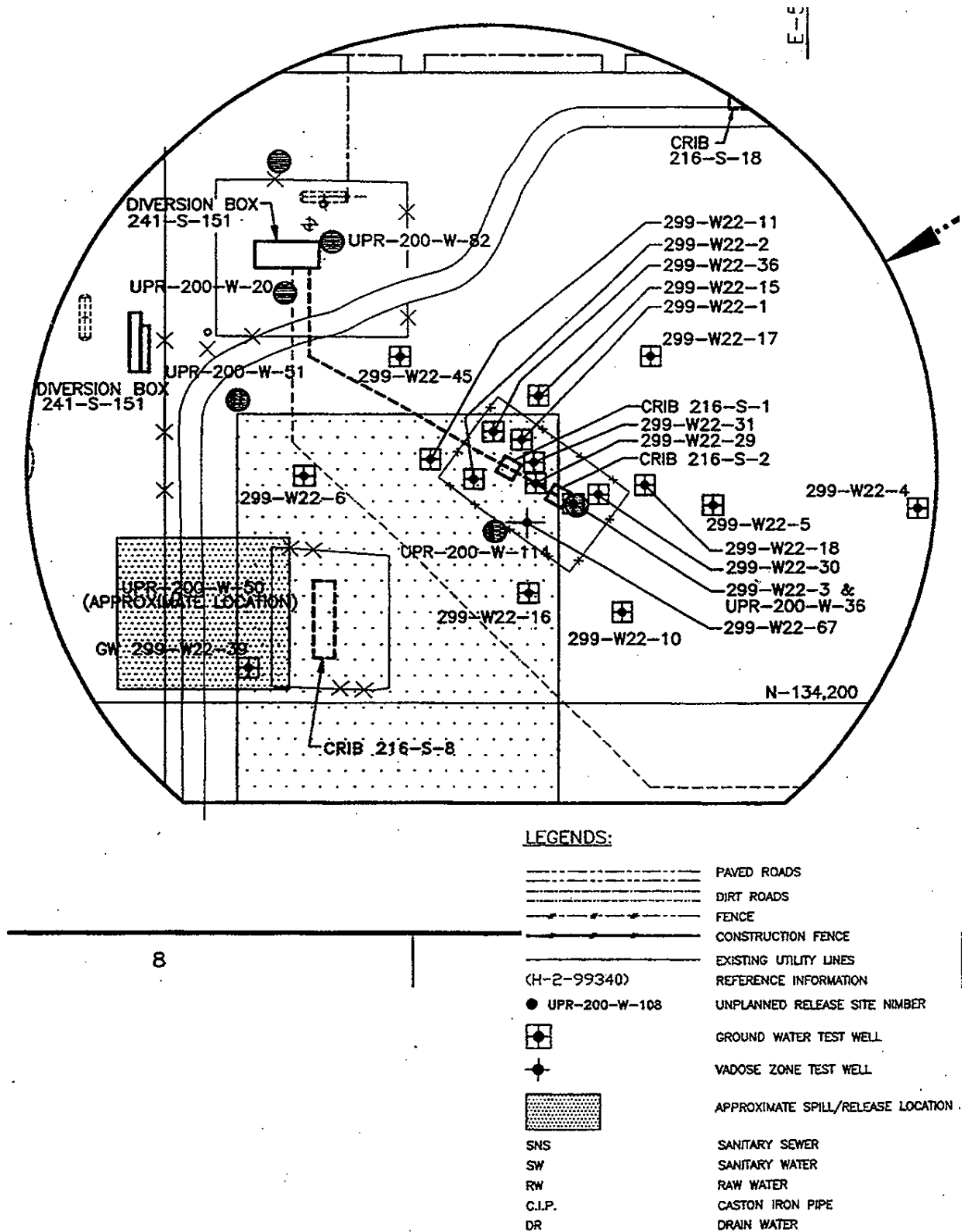


Figure 3-2. Detail of Unplanned Releases in and Around the S/SX Tank Farm Complex (ICF KH 1996).



As discussed in more detail in Section 3.3, gamma activity was monitored in wells within the tank farms. The appearance of, or increase in, gamma activity in a monitoring well would suggest the possibility of a leaking tank (Isaacson and Gasper 1981). The uncertainties associated with using gamma logging methods to detect tank leaks are well documented (Isaacson and Gasper 1981, Isaacson 1982). Even when gamma logging in wells around a specific tank detected radioactivity, an assumption still had to be made as to where the radioactivity originated. Without a focused effort, the exact source of gamma activity located in a monitoring well remained somewhat uncertain.

Given the difficulties in simply identifying a leak in an SST, it is not surprising that estimating the volume of material lost during a leak event is also imprecise (Baumhardt 1989). Except in the cases of the catastrophic leaks in tanks T-106 and SX-115, a large amount of uncertainty exists in the leak volumes listed in the monthly *Waste Tank Summary Report* (Hanlon 1998 and references therein).

The uncertainties associated with the leak detection methods are necessarily imbedded in the list of leaking SSTs in the monthly *Waste Tank Summary Report*. Reviewing many of the references listed in Hanlon (1998) for the SST leaks has led to the conclusion that each tank leak event tends to be unique. The evidence for a leak, volume of waste lost, the waste chemistry, and overall knowledge about the leak and its impacts to the environment are different for each event. As noted in Hanlon (1998), some undocumented leaks from SSTs are likely because of the limitations of the leak detection methods.

The historical documents associated with four tank leak events (A-105, WHC 1991; SX-108, WHC 1992a; SX-109, WHC 1992b; SX-115, WHC 1992c) have been compiled and provide examples of the level of effort required and information available from archived records.

3.2.4 Tank Leak Factors Affecting Vadose Zone

It can be postulated that a number of factors are important in understanding a specific tank-leak event. These may include factors such as leak volume, leak rate, waste chemistry, physical properties of the leaked waste, and soil-waste interactions. However, the amount of information generally available for a leak event is limited. Based on field and laboratory measurements, the waste chemistry, leak rate, and leak volume are available for only two leak events (tanks T-106 and SX-115). Physical properties of leaked waste are not available but can probably be estimated for assumed waste compositions. Thus, realistically, one will be limited to a subset of the wide range of factors that may be important.

Based on a review of the information available from documents referenced in Hanlon (1998), the two factors for which some data exist are leak volume and waste chemistry. The leak volume provided the hydraulic driving force for initial waste movement in the vadose zone and could have sufficiently overwhelmed any geochemical reactivity tending to retard migration of waste in the vadose zone. During a leak event, the physical and chemical characteristics of the leaked fluid are likely to have influenced waste migration. Currently, a major uncertainty in our

understanding of the tank waste-soil interactions is the relationship between the chemistry of the leaked tank waste and tank waste-soil reactions that could impede the migration of radionuclides in the vadose zone. Physical characteristics of the waste that leaked into the soil column may have a large impact on waste mobility.

3.2.5 Specific Tank Leak Events

Leaks from SSTs SX-115 and T-106 were investigated in the 1960's and '70's (shortly after the leak event) using the then-state-of-the-art instrumentation. The reports from these investigations provide a basis for beginning to understand tank-leak events. The leak events investigated generally involved large leak volumes and included extensive gamma logging in both new and then-existing monitoring wells. The third tank leak discussed (U-104) involves one of the first known SST tank leaks and demonstrates the type of assessment that can be constructed from readily available historical data.

3.2.5.1 Tank T-106 Leak. Between April and June of 1973, tank T-106 leaked 435 kL (115,000 gal) of high-level radioactive waste into the vadose zone (Routson et al. 1979). Beginning shortly after the tank leak, additional drywells were installed and gross gamma logging techniques coupled with laboratory gamma energy analysis methods were used to delineate the plume boundary for ^{106}Ru (an assumed mobile radionuclide), ^{144}Ce , and ^{137}Cs (Routson et al. 1979). The waste materials lost to the soil column contained approximately 14,000 Ci of ^{90}Sr , 40,000 Ci of ^{137}Cs , 270,000 Ci of ^{106}Ru and smaller amounts of other short-lived gamma emitters such as ^{144}Ce , ^{125}Sb , and ^{155}Eu , and 4 Ci of plutonium (ARHCO 1973). Based on data in Freeman-Pollard, et al. (1994), the waste also contained 143 Ci of ^{99}Tc and 70 Ci of ^{14}C . Soil contamination was estimated at 25,000 m³ (882,750 ft³) to a depth of 33 m. The base of the initial ^{137}Cs plume was at approximately 15 m (ARHCO 1973).

Based on waste transfer records (Agnew 1995), the waste that leaked from tank T-106 came from the isotope recovery program at B Plant. Given the high levels of ^{106}Ru in the waste when the leak occurred, the waste probably originated from the PUREX acid waste stream and had probably gone through both the ^{137}Cs and ^{90}Sr recovery processes. Thus, the waste would likely have contained high concentrations of organic complexing agents.

In 1978, Routson and coworkers (Routson et al. 1979) published a comprehensive integration of all tank T-106 tank leak studies. This report included the information reported in the 1973 Atlantic Richfield Hanford Company (ARHCO) study plus ongoing gross gamma and spectral gamma logging data. Based on an assessment of all available information, the following conclusions were presented.

- Five years after the leak, the maximum depth of the 1 $\mu\text{Ci/L}$ ^{106}Ru concentration was 33 m (108 ft) below the surface.
- The maximum horizontal extent of the 1 $\mu\text{Ci/L}$ ^{106}Ru concentration was 23 m (75 ft).

- A large portion of the movement occurred in 1973, in the several weeks before the first field investigation.
- From 1973 to 1974, lateral movement occurred in at least some sediment layers in all monitoring wells.
- From 1974 through 1977, waste movement could not be detected.
- Lateral movement noted in three wells in 1977 and 1978 was believed to have been caused by an unusual weather event during the winter of 1977 and 1978.

In response to a General Accounting Office (GAO) recommendation (GAO 1989), a new borehole was drilled in 1993 to evaluate the potential impact of the tank T-106 leak on the unconfined aquifer. The borehole was drilled to 54.8 m (180 ft) deep and 43 split-spoon soil samples were taken for physical, chemical, and radiochemical analyses. Analyses reported include gross alpha, gross beta, total uranium, isotopic plutonium, ^{241}Am , ^{90}Sr , ^{99}Tc , ^{237}Np , gamma energy analysis (GEA), total organic carbon (TOC), semivolatile organics, metals, and general chemical parameters. The data from this investigation, including the geophysical logs for the borehole, are documented in *Engineering Evaluation of the GAO-RECD-89-157, Tank 241-T-106 Vadose Zone Investigation*, BHI-00061 (Freeman-Pollard et al. 1994).

Results from this study, coupled with previous investigations of the tank T-106 leak (Routson et al. 1979), provide the most comprehensive picture of the movement of leaked tank waste through the vadose zone. The results from the 1993 study are covered in Section 3.5.

3.2.5.2 Tank SX-115 Leak. Tank SX-115 was built in 1954 and put into service in 1958; the waste placed inside started boiling in 1959. In 1964, the aged waste was pumped out and condensate was added to dissolve sodium nitrate from the residual solids. In March 1965, tank SX-115 was determined to have leaked about 50,000 gal. In August 1965, 10 test wells were drilled around the tank (Raymond and Shdo 1966). Data from the test wells, coupled with data from existing drywells and laterals, were used to define and characterize the contaminated area under the tank. Approximately 40,000 Ci of ^{137}Cs were lost to the soil column during this leak. Three separate areas of contamination were found. One was completely under the tank; the other two were closer to the edge of the tank with the contaminated zones primarily under the tank.

Interestingly, recent spectral gamma logging investigations (SX tank farm report) in drywells around tank SX-115 reported only a small amount of gamma activity in one drywell even though this is a well-documented leak event (Raymond and Shdo 1966). The drywells used to document the gamma activity plume in 1966 were later abandoned and so were not available for the recent spectral gamma investigation.

It is reasonable to assume tank SX-115 lost its containment integrity (failed) while storing the boiling REDOX waste because low levels of gamma activity were detected in the laterals before the 1965 leak (WHC 1992c). The initial leak could have self-healed, as was reported for other boiling-waste tanks in the SX tank farm (Raymond and Shdo 1966, WHC 1992c).

Experiments have shown that very high levels of dissolved solids in the tank supernatant liquid from the REDOX process would tend to plug tank leaks (Nelson and Knoll 1958). If a tank leak had self-sealed and condensate were added to the tank to recover sodium nitrate, self-sealed leaks would be expected to reopen because the soluble salts (i.e., the salt plug) would be expected to redissolve. As the dilute sodium nitrate solution leaked from the steel liner, it would be expected to transport any concentrated waste outside of the steel liner into the soil column. This leak scenario is consistent with reported data.

3.2.5.3 Tank U-104 Leak. According to Hanlon (1998), tank U-104 was designated as an assumed leaker in 1961, with an estimated leak volume of 208 kL (55,000 gal). However, information from the WSTRS, Rev. 2 (Agnew et al. 1995), indicates that the tank began to leak by 1956. According to the WSTRS, Rev. 2, tank U-104 went into service in 1947 and received metal waste (a byproduct from the first precipitation step in the bismuth phosphate process). Metal waste contained almost all the uranium and 90 percent of the fission products separated from irradiated fuel rods as part of the plutonium recovery process. Tank U-104 is the first in a three-tank cascade with tanks U-105 and U-106 and has a volume of 2006 kL (530,000 gal). The cascade was full by the third quarter of 1948.

In late 1952, sluicing operations to recover metal waste from tank U-104 began. By the end of April 1953, tank U-104 was essentially empty (Rodenhizer 1987). In the fourth quarter of 1954, the cascade was filled with a fresh batch of metal waste. In the first quarter of 1956, sluicing began in tank U-104 to recover the metal waste. Information in WSTRS suggests that about 94.6 kL (25,000 gal) of water were added to tank U-104 as part of the sluicing operations in the second quarter of 1956. During the second sluicing operation, a leak and a bulge in the steel liner on the bottom of the tank were noted.

In the second quarter of 1957, 924 kL (244,000 gal) of water were added to tank U-104 as part of a leak test. Between then and the first quarter of 1961, about 196,841 L (52,000 gal) of liquid (presumably primarily water) leaked from tank U-104 into the vadose zone. During the first quarter of 1961, 481 kL (127,000 gal) of liquid were removed from tank U-104, leaving an estimated waste volume of 254 kL (67,000 gal). In the second quarter of 1965, the waste volume in tank U-104 was estimated to be 57 kL (15,000 gal). Thus, an additional 197 kL (52,000 gal) of liquid (presumably primarily water) apparently leaked between 1961 and 1965.

During the fourth quarter of 1969, 344 kL (91,000 gal) of concentrated supernatant liquid from the 242-T Evaporator were transferred from tank TX-118 to tank U-104. Saltcake would likely have formed from the 242-T Evaporator liquid. Between 1969 and 1972, the waste volume in tank U-104 remained constant at about 401 kL (106,000 gal). In the second quarter of 1972, 60 tons (about 148 kL [39,000 gal]) of diatomaceous earth were added to tank U-104 resulting in a waste volume of about 473 kL (125,000 gal). Hanlon (1988) lists the current waste volume in tank U-104 as about 462 kL (122,000 gal).

Because drywells for gross gamma logging were installed around tank U-104 in the mid-1970's, long after the suspected leaks, gamma logging data are not available for the time the tank leak events occurred. However, the U tank farm was recently evaluated using spectral gamma

logging techniques (DOE-GJO 1997). This study revealed elevated concentrations of ^{235}U , ^{238}U , and ^{137}Cs in drywells around tank U-104. The presence of uranium in the vadose zone would suggest that the source was metal waste (from the Bismuth Phosphate process) rather than some other waste stream added to the tank at a later date.

Based on this information, one can speculate that tank U-104 probably failed shortly after being refilled with metal waste in 1954. Some of the metal waste probably was lost to the vadose zone at that point. After concentrated supernatant liquid from the 242-T Evaporator was added, no additional losses were observed.

3.2.6 Tank Leak Summary

A summary of the information about SST leaks is published in the monthly *Waste Tank Summary Report* (Hanlon 1998). Although this summary is extensively referenced, a comprehensive document integrating what is known about SST leaks is not available. However, as previously discussed, detailed histories of leaks are available for SSTs T-106, A-105, SX-108, SX-109, and SX-115. The knowledge base for other SST leaks varies significantly. Even though extensive leak detection programs were in place, in many cases, providing unequivocal evidence for a leak from a specific tank proved elusive. Under these circumstances, developing reliable leak volume estimates is impossible. Thus, 19 tanks are listed in Hanlon (1998) as "confirmed or assumed" leakers without leak volume estimates.

An examination of the references listed in Hanlon (1998) reveals some patterns in SST leaks. The SX tank farm contains 15 SSTs, each with a nominal 1-million-gallon storage capacity. Tanks SX-105 and SX-107 through SX-115 were designed to receive REDOX high-level self-boiling waste. According to Hanlon (1998), nine of the SX tanks that received self-boiling waste are assumed leakers. At least two distinct types of waste leaks are believed to have occurred in the SX tank farm. Leaks from tanks containing self-boiling waste would have involved the loss of waste material with the characteristics of high temperature, high pH, high aluminum, and high ionic strength. However, leaks from SX-113 and SX-115 involved a more dilute sodium nitrate solution with (presumably) lower levels of radionuclides.

In at least four tanks (SX-115, SX-113, SX-108, and U-104), the leaks were observed after water was added. In these four cases, the initial tank leaks probably self-sealed because of the high levels of dissolved solids in the tank liquids. Adding water or any other dilute liquid to any tank with self-sealed leaks would tend to dissolve any soluble salts that had plugged the leak. Historical tank leak documentation contains frequent references to tank leaks self-sealing (Raymond and Shdo 1966, Womack and Larkin 1971, WHC 1992). Thus, assuming that temporary seals would form any time highly concentrated tank supernatant liquid was leaking into the vadose zone is realistic.

Major leaks occurred in tanks T-106 and BX-102 shortly after large volumes of supernatant liquid were transferred into tanks that had been nearly empty for years (Routson et al. 1979, Womack and Larkin 1971).

3.3 GAMMA-RAY LOGGING INFORMATION

Since the 1960's, gross gamma logging has been conducted in monitoring wells (drywells) around tanks in the SST farms both regularly and as needed (Isaacson and Gasper 1981, Welty 1988). Selected tanks in two farms also had laterals under the tanks for monitoring gamma activity. Only limited analysis has been done on the historical monitoring data. These data show the history of contaminant migration and, occasionally, the beginning of a leak (Isaacson and Gasper 1981). When analyzed, these data are anticipated to provide an essential element in assessing contaminant migration. Data derived from these logging campaigns through the early 1970's were maintained as paper analog records. Data derived since 1974 have been stored digitally and are available from the Hanford Site local area network (HLAN) using the following drive path: \\sacs\cass\drywells. However, most of the early leak history appears to fall within the time frame of the non-digitized information.

The gamma logs were collected as part of the secondary leak-detection system using a variety of tools with a range of sensitivity (Isaacson and Gasper 1981, Welty 1988). In general, these tools were run at an uphole logging speed of about 14 m/min (45 ft/min). Logs were often run as frequently as weekly. These logs were examined immediately after being taken and assessed to ascertain whether the leak detection criteria were exceeded. If the logs did not exceed the established criteria they were archived and not reviewed further. If the logs exceeded the established criteria other tank data were analyzed to determine if the tank was indeed leaking.

In 1995, a baseline spectral gamma logging program of all of the drywells in SST farms was initiated by Mactec-ERS and its predecessor, Rust Geotech, through the U.S. Department of Energy, Grand Junction Project Office (DOE-GJPO). Spectral gamma logging techniques provide information on quantities of specific gamma-emitting radionuclides. Gamma spectra were collected at 0.5 ft intervals over the depth of the tank farm drywells. Counting time at each interval averages 100 seconds. A high-purity germanium (HpGe) detector was used in this effort. Baseline spectral gamma logging has been completed in most of the SST farms. Results of these efforts are available in tank farm reports and individual tank reports.

The availability of digitized historical data has presented an opportunity to perform analyses beyond those for which the data were originally collected. The data from the gamma logs routinely collected over 20 plus years are the key to discovering how gamma-emitting contaminants have moved through the subsurface. By ascertaining when these contaminants moved, the drivers that caused the movement probably can be determined. Differences in the rate or timing of movement from various farms will provide additional insight into controlling factors such as leak volume, waste chemistry, or geology. Coupling historical gamma logging data with speciation data from spectral gamma logging results and waste chemistry at the time of tank leaks may be a way to successfully identify sources of radioactive waste plumes in tank farms and the time frames they were produced (see Section 3.3.3).

However, limitations are associated with gamma-ray logging techniques. The gamma logging techniques provide no direct information about the non-gamma-emitting long-lived mobile radionuclides such as ⁹⁹Tc and ¹²⁹I. The gamma logging data are further limited by the

availability of boreholes and the fact that gamma rays are completely attenuated by 30 cm to 46 cm (12 to 18 in.) of soil. Thus, large tank leaks could have been missed because of the location of available monitoring wells.

3.3.1 Access to Gamma Logging Data

Gross gamma logging data for the period between 1974 and 1994 are available electronically on the HLAN. These data are arranged by tank farm, then by tank, and finally by the date the log was collected. The numerical file indicates the class of instrument used and whether the log file is an original or a confirmatory rerun. Measurements are reported as gross count rates taken at 0.3 m (1-ft) intervals. Pre-1974 data are more difficult to access since they are generally archived. Recent efforts have demonstrated that historical hard-copy files can be retrieved, if required. In addition to these published documents, electronic copies of spectral gamma logging information are available through Mactec-ERS.

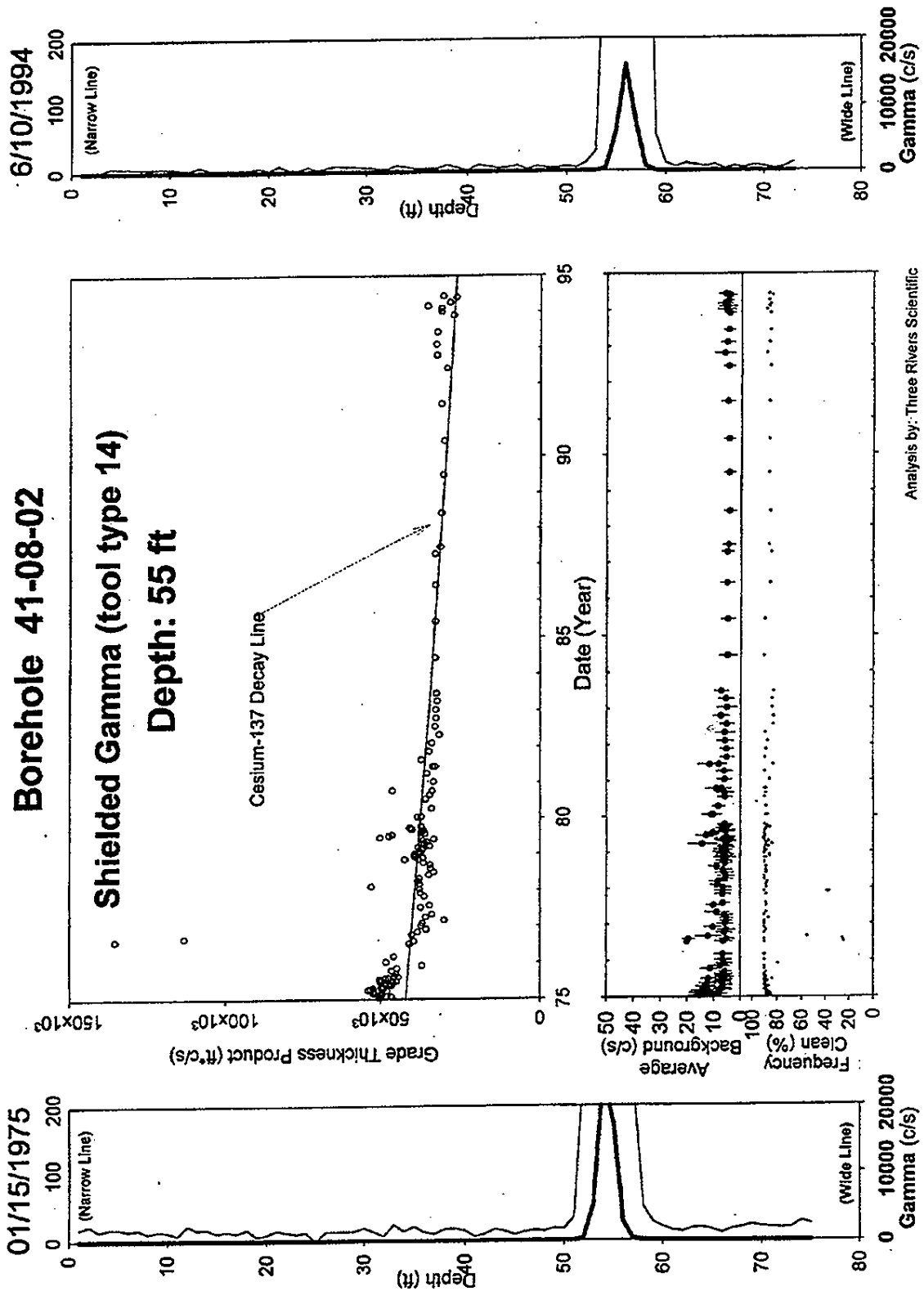
3.3.2 Data Analysis

Elements integral to analyzing historical gamma logging data include the following:

- Assessment of Tool Application. Different tools used throughout the monitoring history present different responses to gamma-emitting contaminant concentrations.
- Assessment of the database to identify clear errors in borehole identification.
- Development of the gradient-thickness product to account for the inventory and distribution of contaminants through time, and to account for errors in depth measurement.

Applying the gradient-thickness product effectively removes discrepancies in the historical data caused by shifting of the depth datum. This product can be used to ascertain whether contaminant concentrations are increasing, decreasing, or remaining stable relative to decay of the predominant radionuclide present. Gradient thickness product plots that show an increase above the decay rate indicate that contaminant concentrations are increasing. A decrease greater than the decay rate of the predominant radionuclide indicates movement through a zone. An increasing zone at depth in parallel with a decreasing zone above indicates vertical movement in the vicinity of the well; an increase at depth with no decrease above indicates lateral movement. A gradient thickness product plot is shown in Figure 3-3.

Figure 3-3. Gradient Thickness Product Plot.



Analyzing the background count rate provides a quality assurance review of the data, ensuring that the instruments and readings are compatible over the period of record. Development "stack-plots" (time-series plots) help to visually depict the stability or instability of contaminants within a depth profile. A sample stack plot is shown in Figure 3-4.

Spectral gamma information available through DOE-GJPO provides a current analysis of the depth and concentration distribution of gamma-emitting radionuclides at boreholes throughout the SST farms. These interpretations are used to "ground-truth" the historical gross gamma logs and to provide the baseline against which future assessments can be made. Because of the limitations of the current spectral probe (HPGe), concentrations of contaminants in excess of 10^4 pCi/g cannot be determined. A cadmium-zinc-telluride (CZT) probe is being developed to increase the range of concentrations that can be assayed.

3.3.3 Results of Analysis of Historical Gamma Logging Data from SX Tank Farm

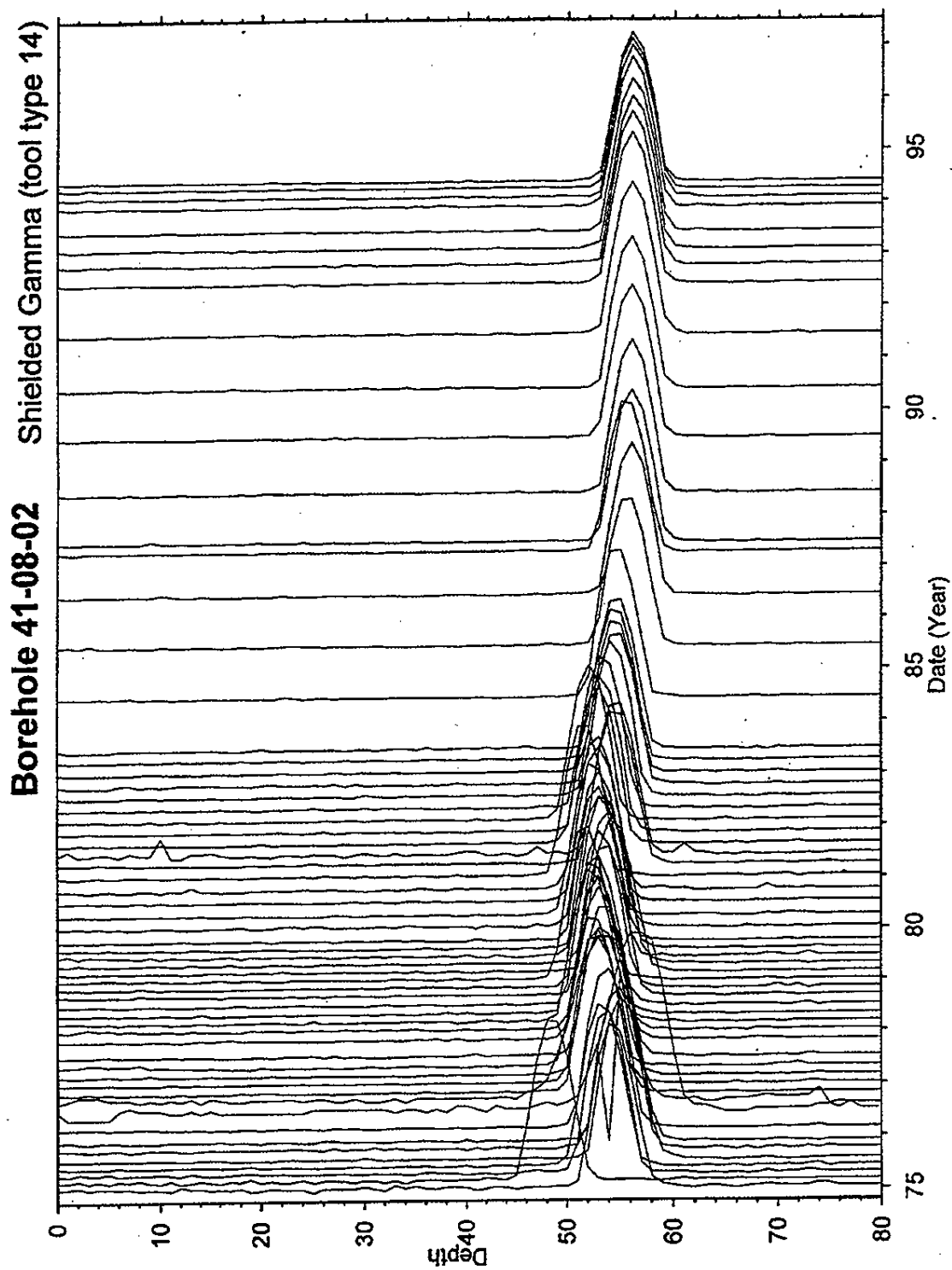
Historical gamma logging results from 98 drywells located in the SX tank farm collected between 1974 and 1994 were analyzed and reported in the *Fiscal Year Waste Information Requirements Document*, HNF-3136 (Adams 1998). The dominant gamma-emitting radionuclide encountered was ^{137}Cs . Thirty-five of the 98 drywells were clean. Eighty-three contamination zones were identified in the remaining 63 wells. Analysis of the gradient thickness product plots indicated that the radioactivity in 41 of the contaminated zones was decaying at the rate expected for ^{137}Cs . In 11 of the contaminated zones, the radioactivity was decreasing at a rate less than would be expected for ^{137}Cs . Thus, in these 11 zones, ^{137}Cs probably was still moving in the zone while the measurements were being taken. Within the precision of the data, the status of 29 of the contaminated zones could not be assigned as "stable" or "changing." Interestingly, no evidence was found of downward migration of any of the contaminated zones in the SX tank farm.

3.4 GROUNDWATER MONITORING DATA

This section summarizes documents that evaluate groundwater contamination data from samples collected near tank farms. In these documents, potential sources of contamination are considered and various lines of evidence indicating a potential source are provided. Tank leaks include leaks from a tank itself as well as from related sources (surface spills, runoff from water line ruptures, transfer lines, diversion boxes, valve pits, and the saltwell pumping pipeline). Groundwater contamination from these tank-related sources could be virtually indistinguishable from a tank leak itself.

The following summary of groundwater assessments for tank farms is based on recent studies (Johnson and Chou 1998, Hodges 1998, Narbutovskih 1998, and Hartman and Dresel 1997). The results of groundwater quality assessments for the S-SX, T-TX-TY, and B-BX-BY tank farms are presented in Sections 3.4.1 through 3.4.3.

Figure 3-4. Sample Stack Plot.



3.4.1 S-SX Tank Farms

The groundwater monitoring well network in the vicinity of the S-SX tank farms is shown in Figure 3-5. Groundwater monitoring assessment was triggered in 1996 when a high concentration of ^{99}Tc was found in downgradient wells.

Groundwater flow direction beneath the S-SX tanks is toward the southeast. The water table elevation is approximately 138 m to 139 m above mean sea level (amsl). Figure 3-6a shows the water table elevation at well 299-W23-4 (approximately 90 m west of the WMA S-SX boundary; see Figure 3-5), between 1966 and 1994. The water table elevation was about 7 m higher until 1986 when it began to decline steadily. Figure 3-6b shows that five representative S-SX monitoring wells exhibit about the same rate of decline (approximately 0.5 m/yr) since 1991. The groundwater gradient is about 0.002, velocity ranges from 0.004 to 0.55 m/d, and saturated hydraulic conductivity ranges from 0.43 to 27.3 m/d (Hartman and Dresel 1997), indicating a highly transmissive aquifer.

Figure 3-7 shows ^{99}Tc , chromate, and nitrate levels in six S-SX monitoring wells between 1991 to 1997. All three constituents show increasing trends over time in both wells 299-W23-15 and 299-W22-46 (see Figure 3-5 for locations). The abrupt increases in all three contaminants that began to emerge for well 299-W22-46 in 1997 mimic patterns observed in well 299-W23-15 from 1992 to 1993 (Johnson and Chou 1998). Peak concentrations for all contaminants occur in well 299-W23-15 during early 1993 and decline as the plume passes the well. By the end of 1995 all three contaminants are increasing in well 299-W22-46, suggesting that the plume has moved from west to east.

Figure 3-8 shows the 1991 to 1997 tritium concentrations for the six wells shown in Figure 3-7. The tritium concentration levels shown in Figure 3-8 display a different trend from those of ^{99}Tc shown in Figure 3-7. This suggests that ^{99}Tc and ^3H are derived from different sources. The tritium concentration is much higher in the upgradient well (299-W23-14) than in downgradient wells (Figure 3-8). The most likely source of the tritium is the 216-S-21 crib that received nearly 100 000 kL of tank condensate containing tritium (Johnson and Chou 1998). The tritium concentration at well 299-W22-15 may have declined because groundwater flow changed direction as the U Pond mound dissipated.

Figure 3-9 shows the ^3H -technetium concentration ratios versus ^{99}Tc concentration for the wells near the S-SX tank farm (Johnson and Chou 1998). The solid line (Figure 3-9) shows an initial high ^3H concentration relative to a low ^{99}Tc concentration in upgradient wells. The very high tritium and very low ^{99}Tc concentrations in upgradient wells reflect the separation of tritium as tritiated water vapor from the high-salt, self-boiling S-SX tank waste, and its subsequent discharge to adjacent cribs. Both lines in Figure 3-9 appear to systematically approach a ratio of about 1:10, consistent with a tank or tank-related source. If upgradient sources were responsible for the ^{99}Tc plume in the groundwater beneath the S-SX tank farm, the ratio should be somewhat uniform for wells both upgradient and downgradient. The dramatically lower ^3H -technetium ratio in the downgradient wells is attributed to an increased concentration of ^{99}Tc from a tank or tank-related source (Johnson and Chou 1998).

Figure 3-5. Groundwater Monitoring Well Network Near the S-SX Tank Farms.

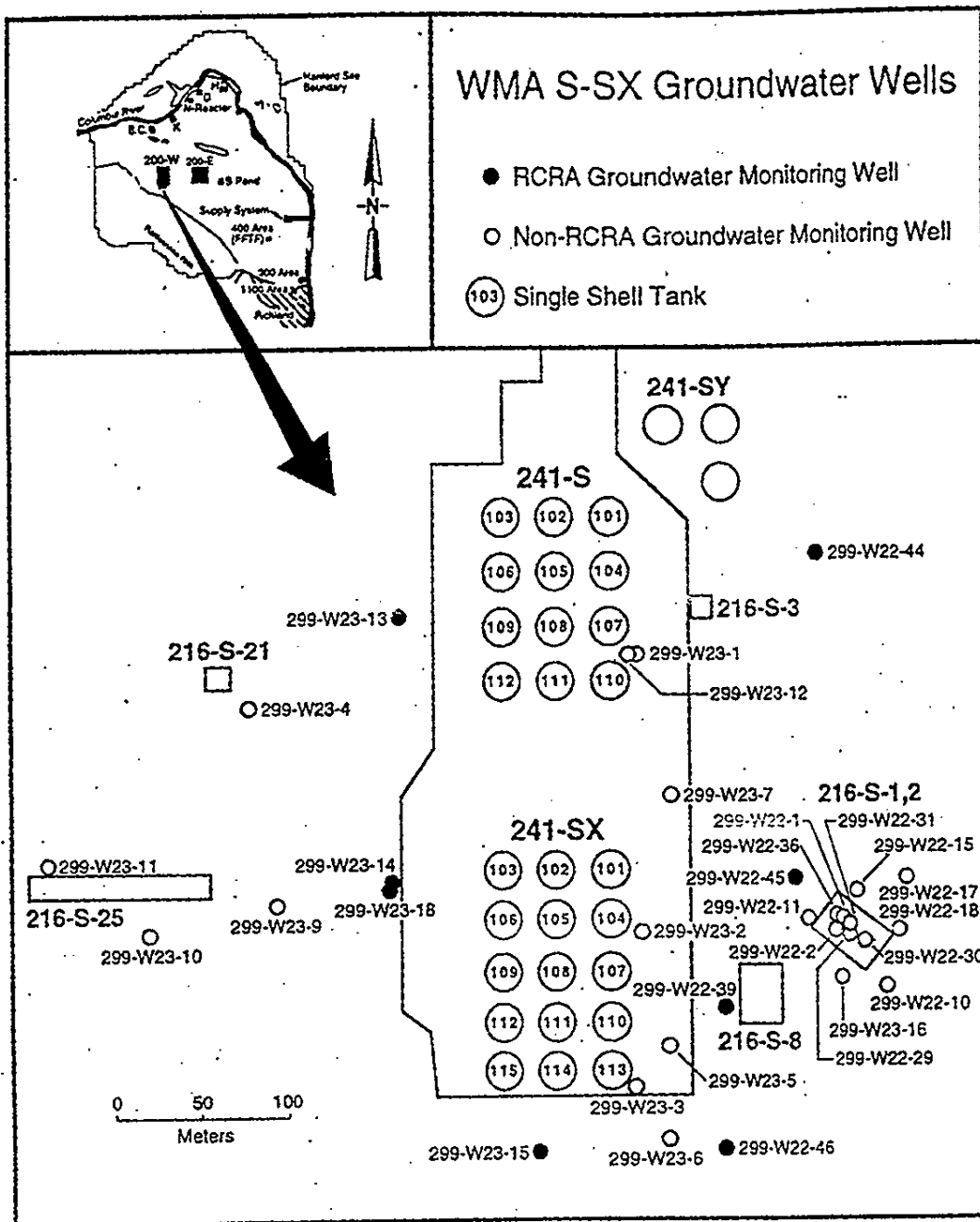


Figure 3-6a. Water-Table Elevations in Well 299-W-23-4 (see Figure 3-5 for Well Location) (after Hartman and Dresel 1997).

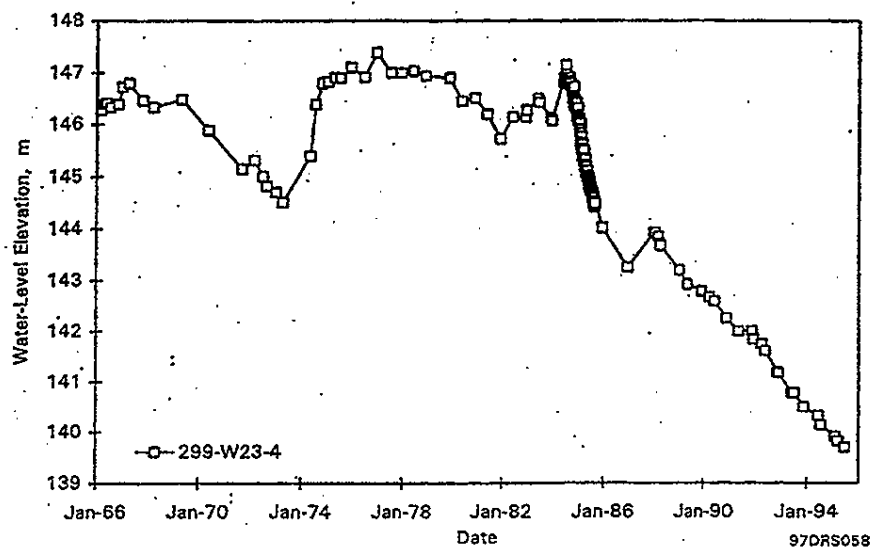


Figure 3-6b. Water-Table Elevations in Wells Monitoring WMA-S-SX Single-Shell Tank Farms (see Figure 3-5 for Well Location) (after Hartman and Dresel 1997).

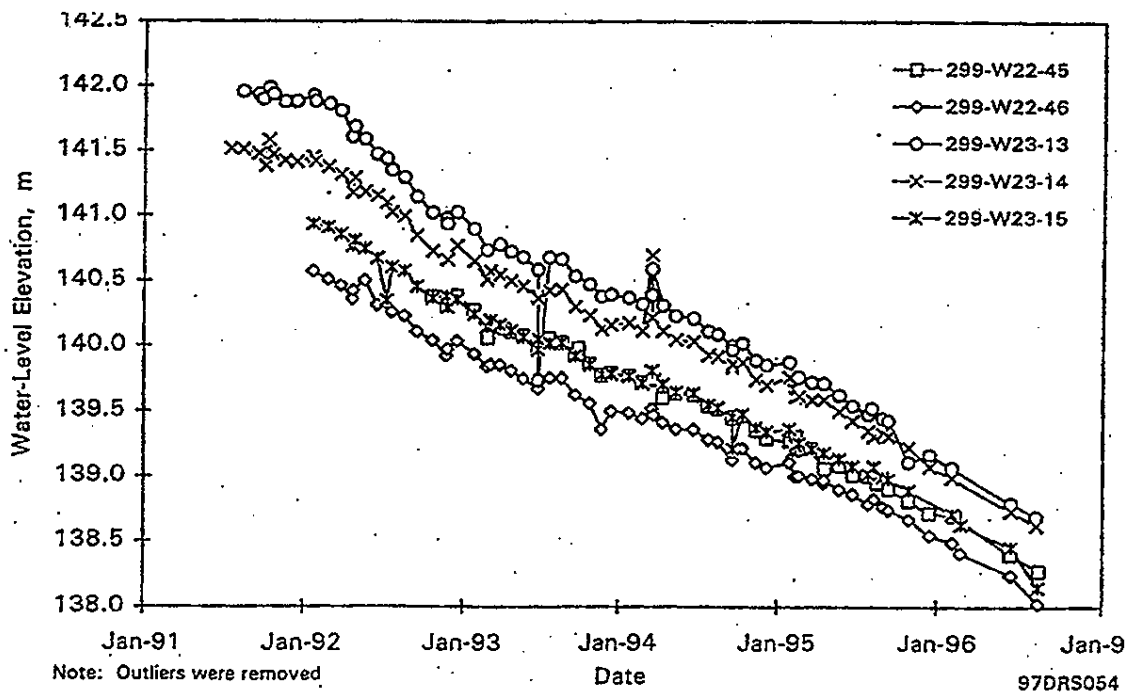


Figure 3-7. Time Series Plots of ^{99}Tc , Chromium, and Nitrate in the Waste Management Areas S-SX Monitoring Well Network (after Johnson and Chou 1998). (Concentrations of chromate are in micrograms per liter of chromium, as reported by the vendor; $\mu\text{g/L}$ of $\text{CrO}_4 = 2.28 \times \text{Cr}$.) (See Figure 3-5 for well locations.)

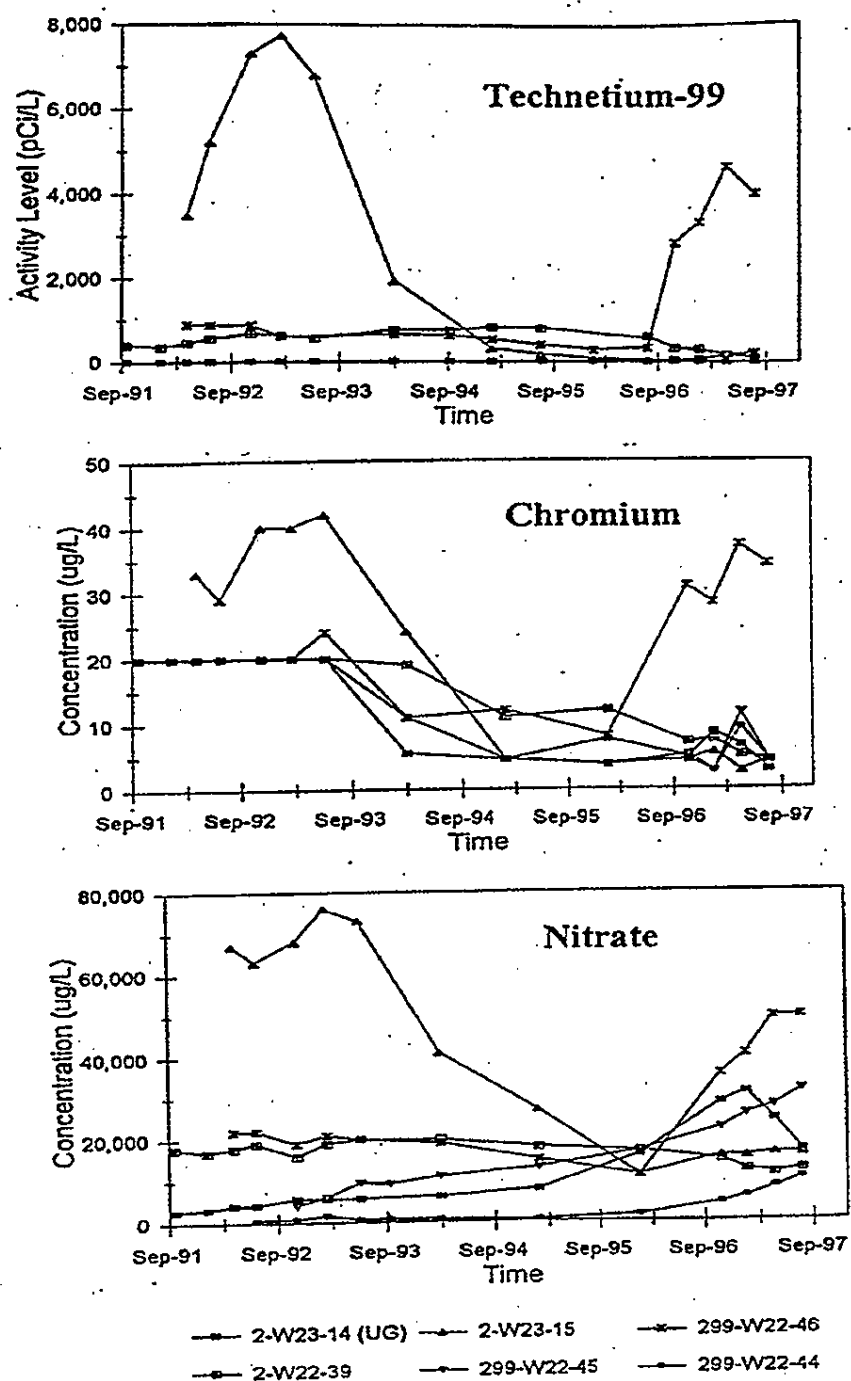


Figure 3-8. Tritium Concentrations versus Time in Waste Management Areas
S-SX RCRA Monitoring Well Network (after Johnson and Chou 1998).
(See Figure 3-5 for well locations.)

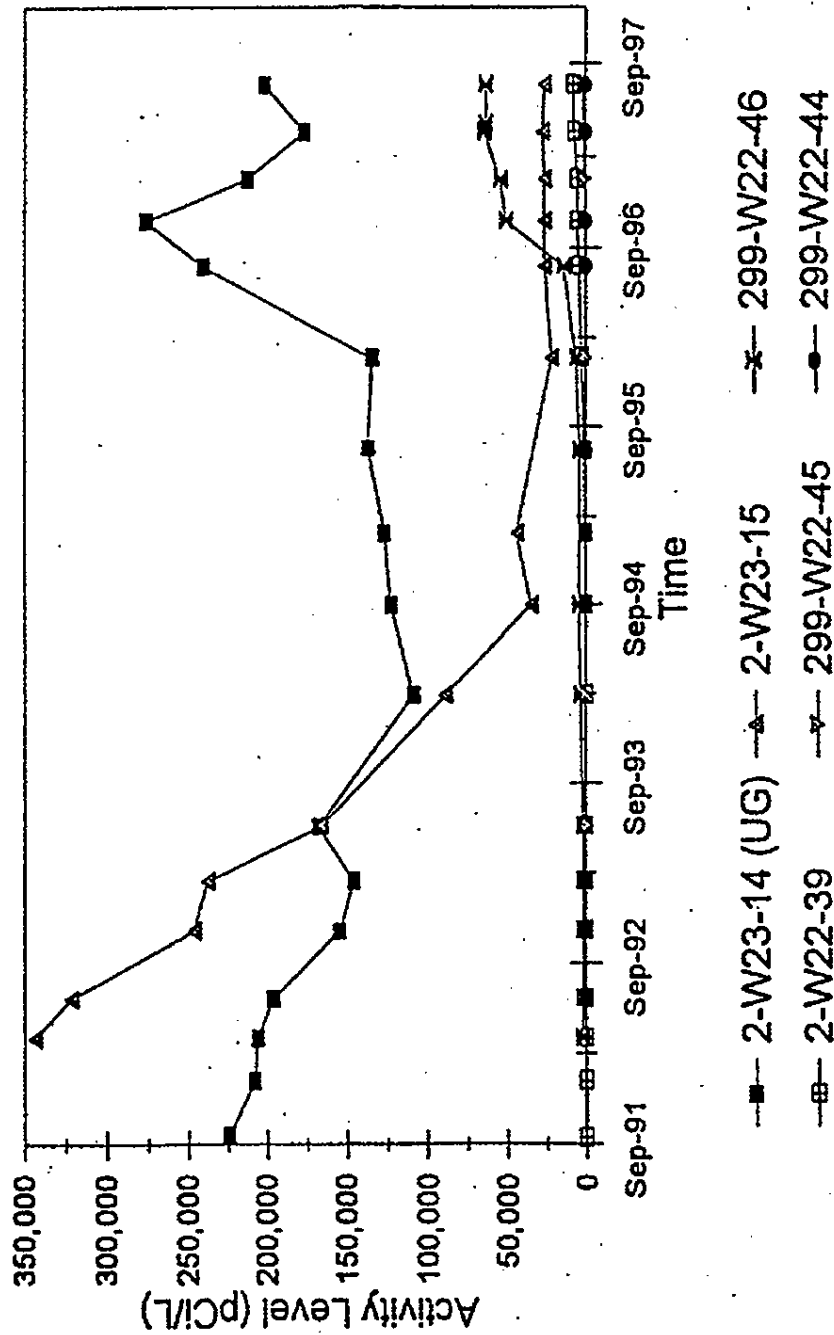
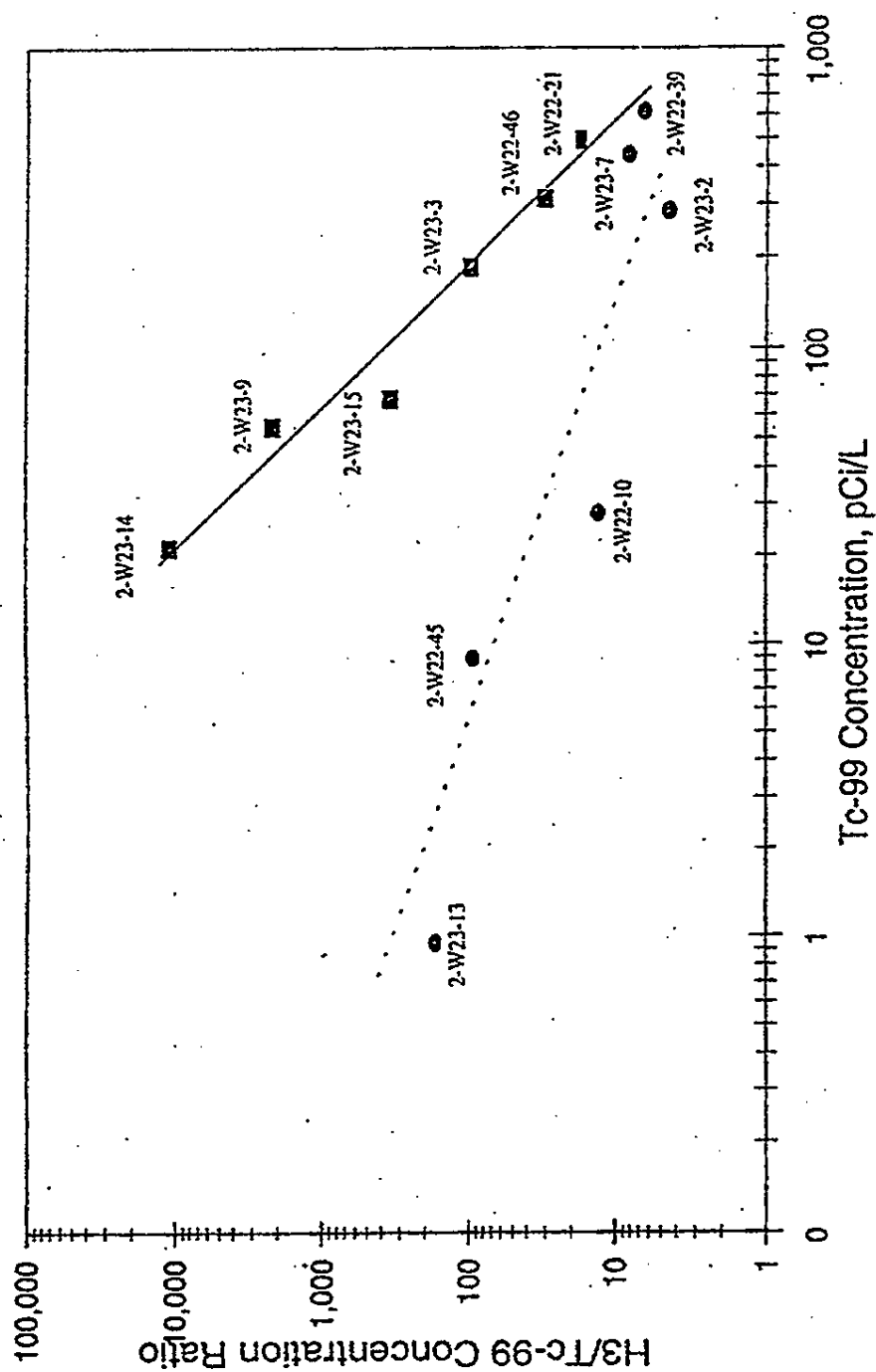


Figure 3-9. Tritium/Technetium Ratio versus Technetium Concentration in Selected Wells (after Johnson and Chou 1998). (Data shown are the 1996 average values for 12 wells in the immediate vicinity of Waste Management Area S-SX.) (See Figure 3-5 for specific well locations.) (The two straight lines are a best visual linear fit to the data points.)



The technetium-uranium ratio may be another indicator of origin for a contaminant plume. Johnson and Chou (1998) proposed that tank waste has a technetium-uranium ratio of more than 300, while the ratio for cribs is less than 0.1. Figure 3-10 shows a region with a technetium-uranium ratio of more than 50 located in the tank farm. This further supports the contention that waste from tanks or tank-related sources has reached the groundwater. However, Johnson and Chou were unable to identify which tank leak or tank-related event was responsible.

3.4.2 T-TX-TY Tank Farms

Figure 3-11 shows the location of monitoring wells, cribs, trenches, and tile fields in the T-TX-TY tank farms. The present groundwater flow direction beneath the T-TX-TY tanks is toward the northeast. Figures 3-12a and 3-12b show the water level elevation for the T and TX-TY tank farms, respectively. Both figures show that the water level has been declining since 1991. The water level declined about 3 m between 1991 and 1997. The rate of decline increased for all wells from 1995 to 1996.

The observed ^3H -technetium ratio as a function of ^{99}Tc concentration for T tank farm wells is shown in Figure 3-13. The ^3H -technetium ratios for the T tank farm define two groupings, indicating contributions from separate sources. Wells 299-W10-15, 299-W10-16, and 299-W11-28 follow a line of high tritium that suggests contamination from discharges in adjacent cribs, trenches, and tile fields. Well 299-W11-27 concentrations initially follow a line of low tritium and high ^{99}Tc offset from, but parallel to, the line of the other three wells. Well 299-W11-27 data represent two trends; one for 1992 through mid-1995 and the other for late 1995 to the present. The post-1995 trend is toward higher ^{99}Tc concentrations and asymptotes toward the tank composition for ^{99}Tc and ^3H -technetium ratios. Hodges (1998) notes that the break in the line and the significant rise in ^{99}Tc concentration coincide with the cessation of surface water discharges in the 200 West Area in mid 1995.

Figure 3-14 shows the high degree of correlation between ^{99}Tc and its cocontaminants (nitrate, ^3H , ^{129}I , and ^{60}Co) in well 299-W14-12 downgradient of the TX tank farm. The high degree of correlation indicates a common source for all the contaminants. As with the T tank farm, observed ^3H -technetium ratios for the TX-TY tank farms define two groupings, indicating contributions from separate sources (Figure 3-15). Wells 299-W10-17, 299-W10-18, and 299-W15-22 follow a line that suggests contamination from discharges in adjacent cribs and trenches. Well 299-W14-12 defines a line that diverges from that of the other three wells toward the composition of tank waste (Figure 3-13).

Figure 3-10. Technetium-Uranium Ratio in Groundwater Near Waste Management Areas S-SX (after Johnson and Chou 1998).

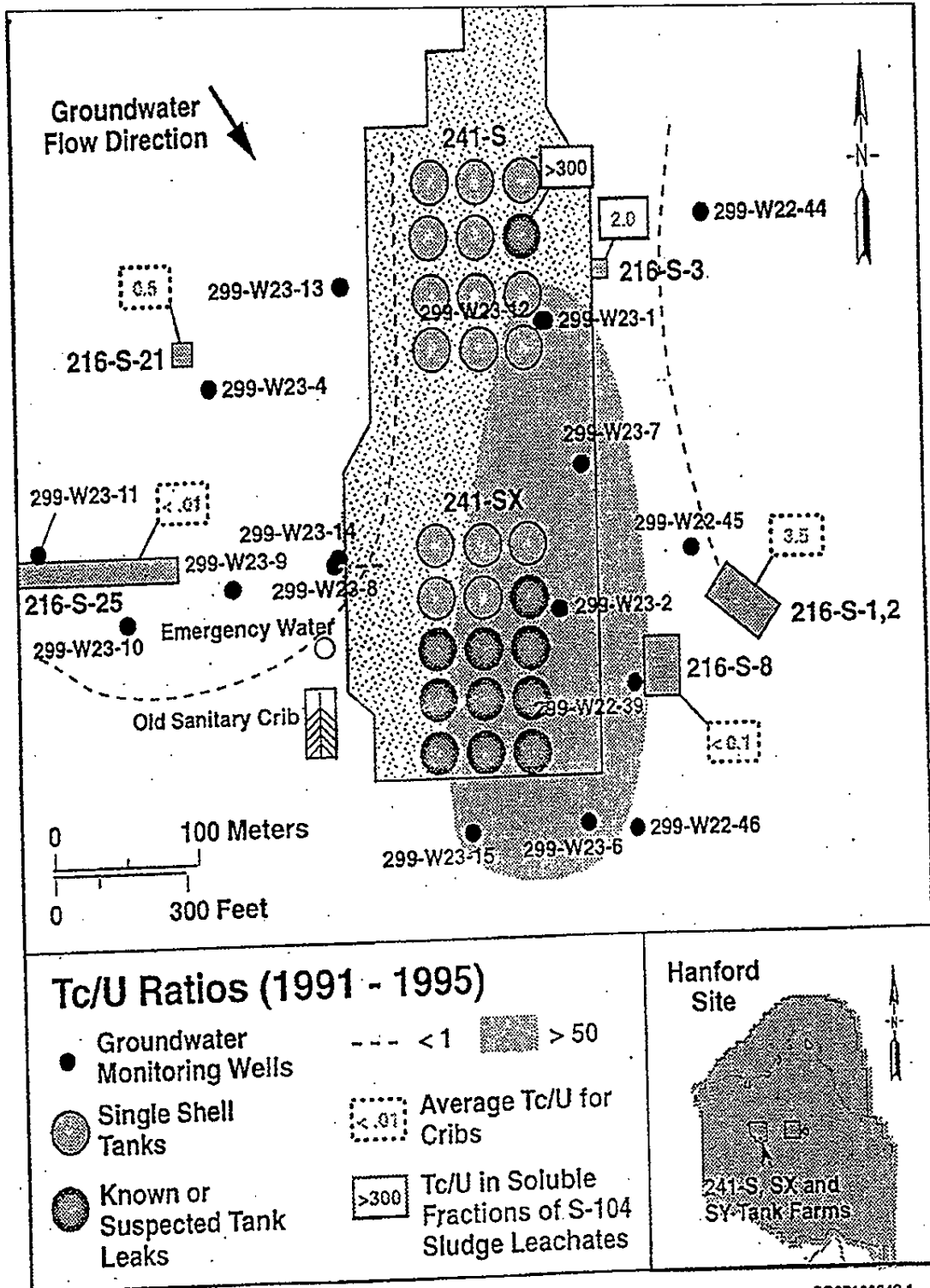


Figure 3-11. Waste Management Areas T and TX-TY Monitoring Network and Adjacent Facilities and Wells (after Hodges 1998).

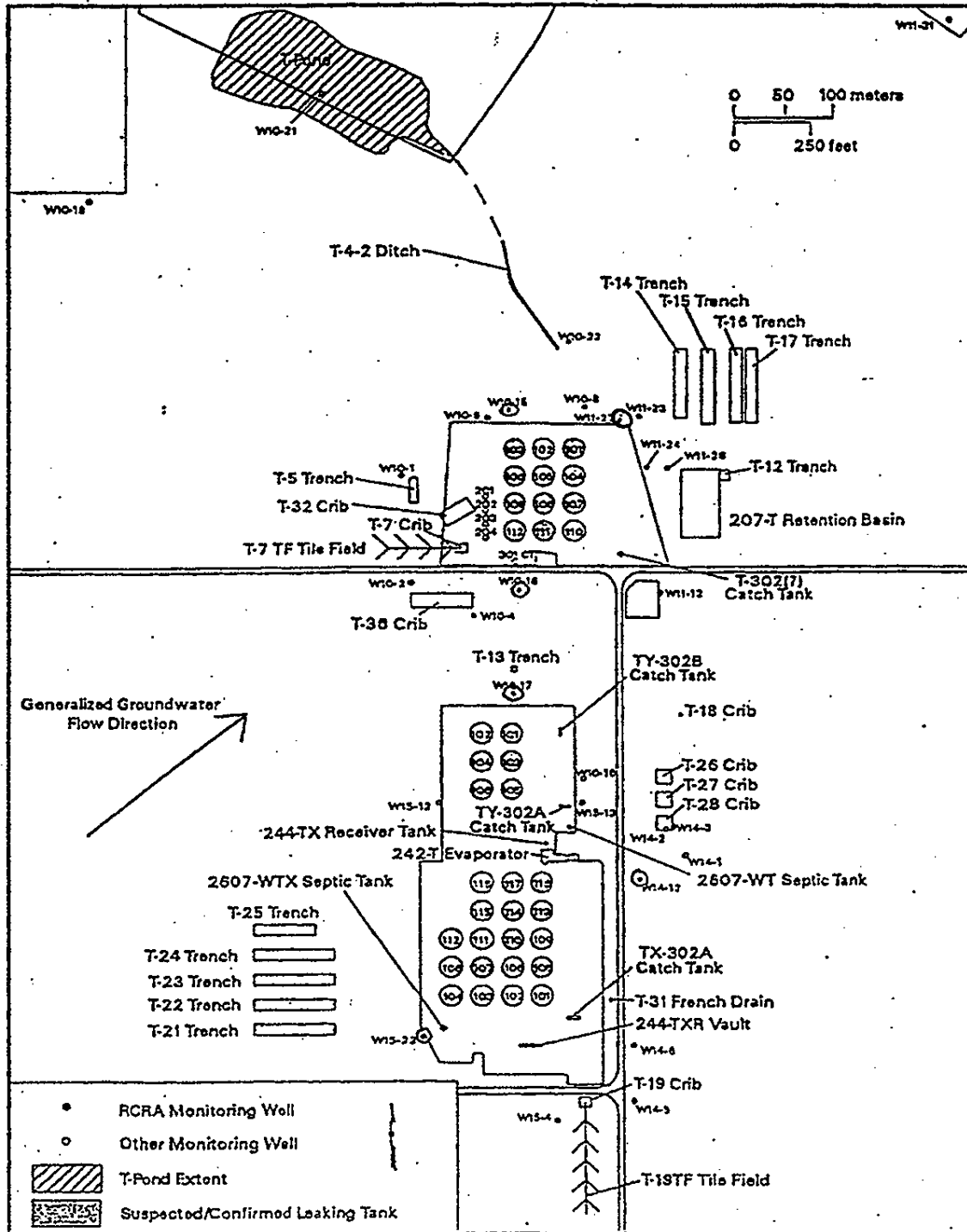


Figure 3-12a. Water-Table Elevations in Wells Monitoring Waste Management Area T Single-Shell Tank Farm (after Hartman and Dresel 1997).

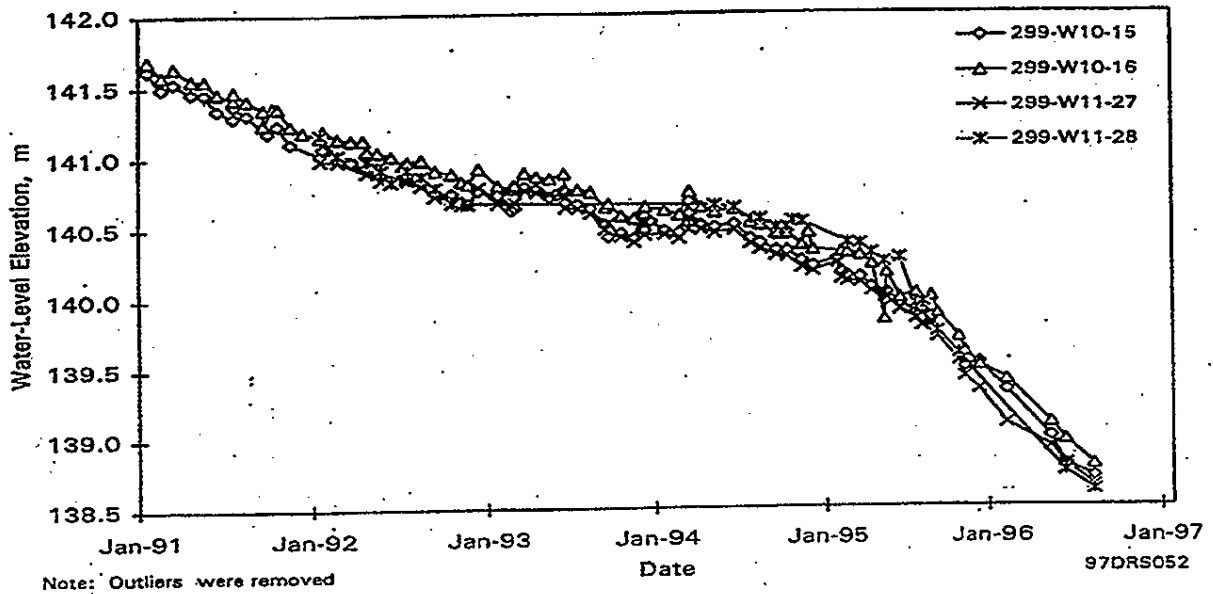


Figure 3-12b. Water-Table Elevations in Wells Monitoring Waste Management Areas TX-TY Single-Shell Tank Farm (after Hartman and Dresel 1997).

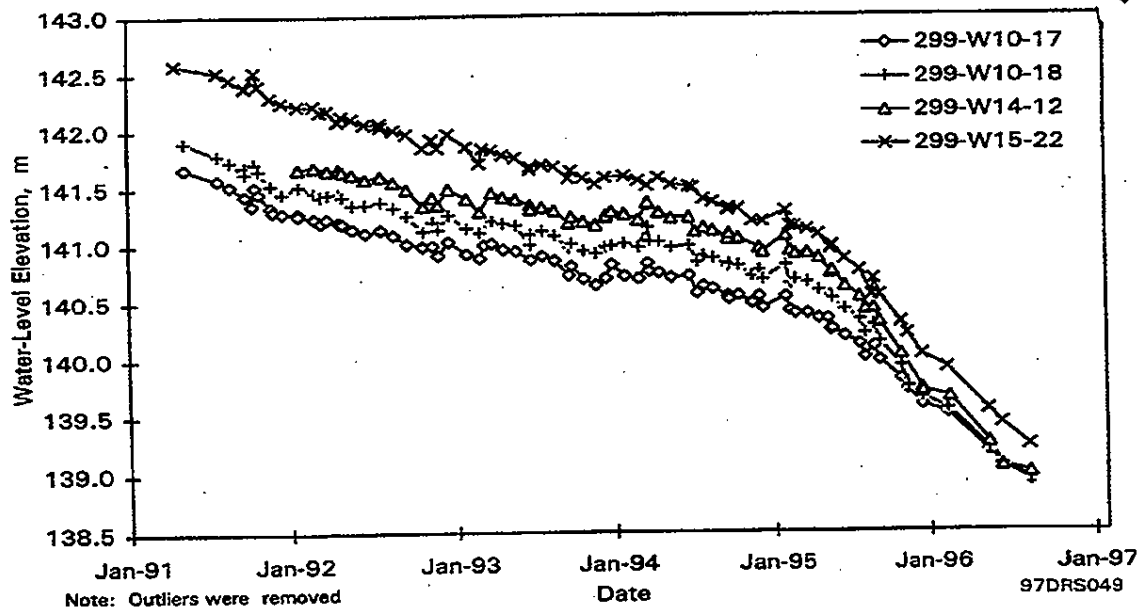


Figure 3-13. Plot of Tritium/Techetium-99 versus Technetium-99 for Wells at Waste Management Area T. (Well 299-W10-16-22 is the Upgradient Well.) (See Figure 3-11 for well locations.) (Tank data from Agnew [1997] [after Hodges 1998]).

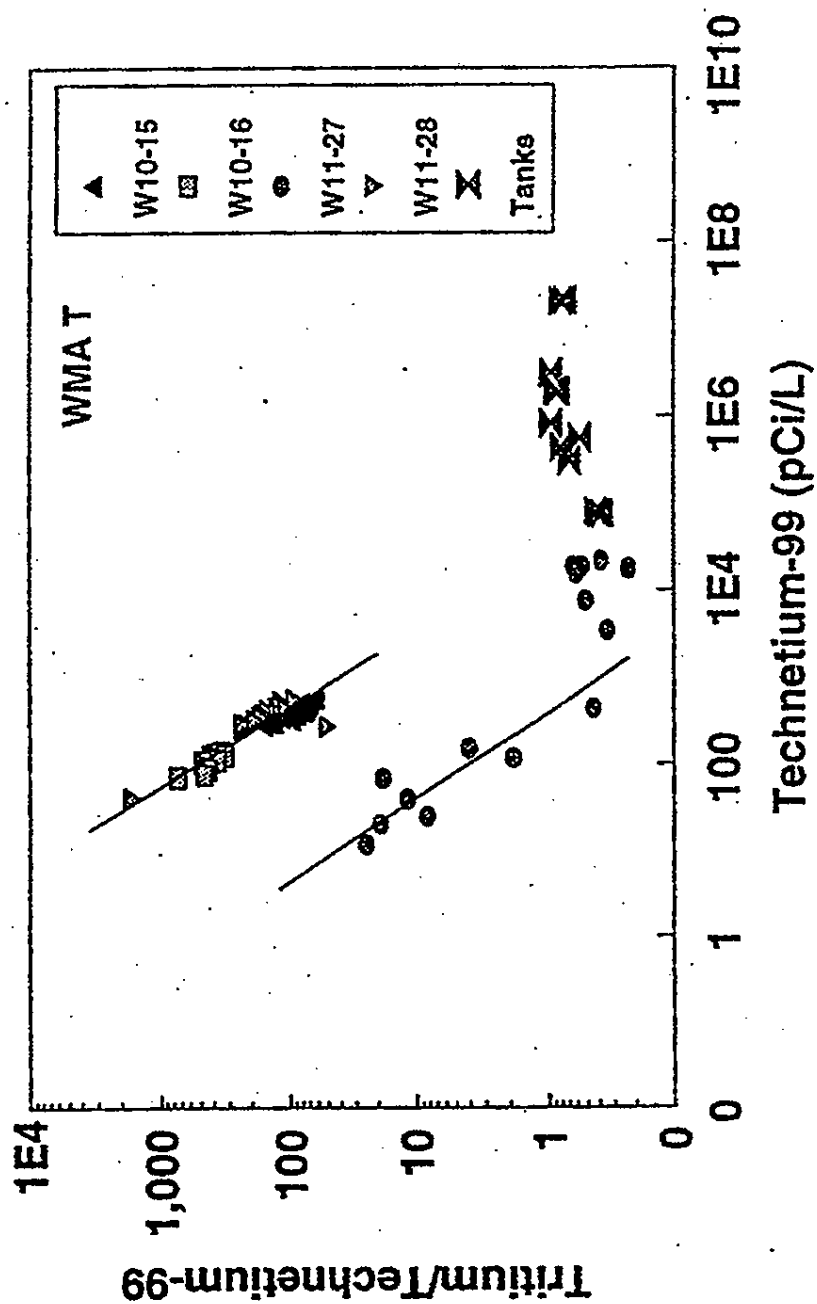


Figure 3-14. Plots of Technetium-99 versus (a) Tritium, (b) Nitrate, (c) Iodine-129, and (d) Cobalt in Well 299-W14-12 (after Hodges 1998).

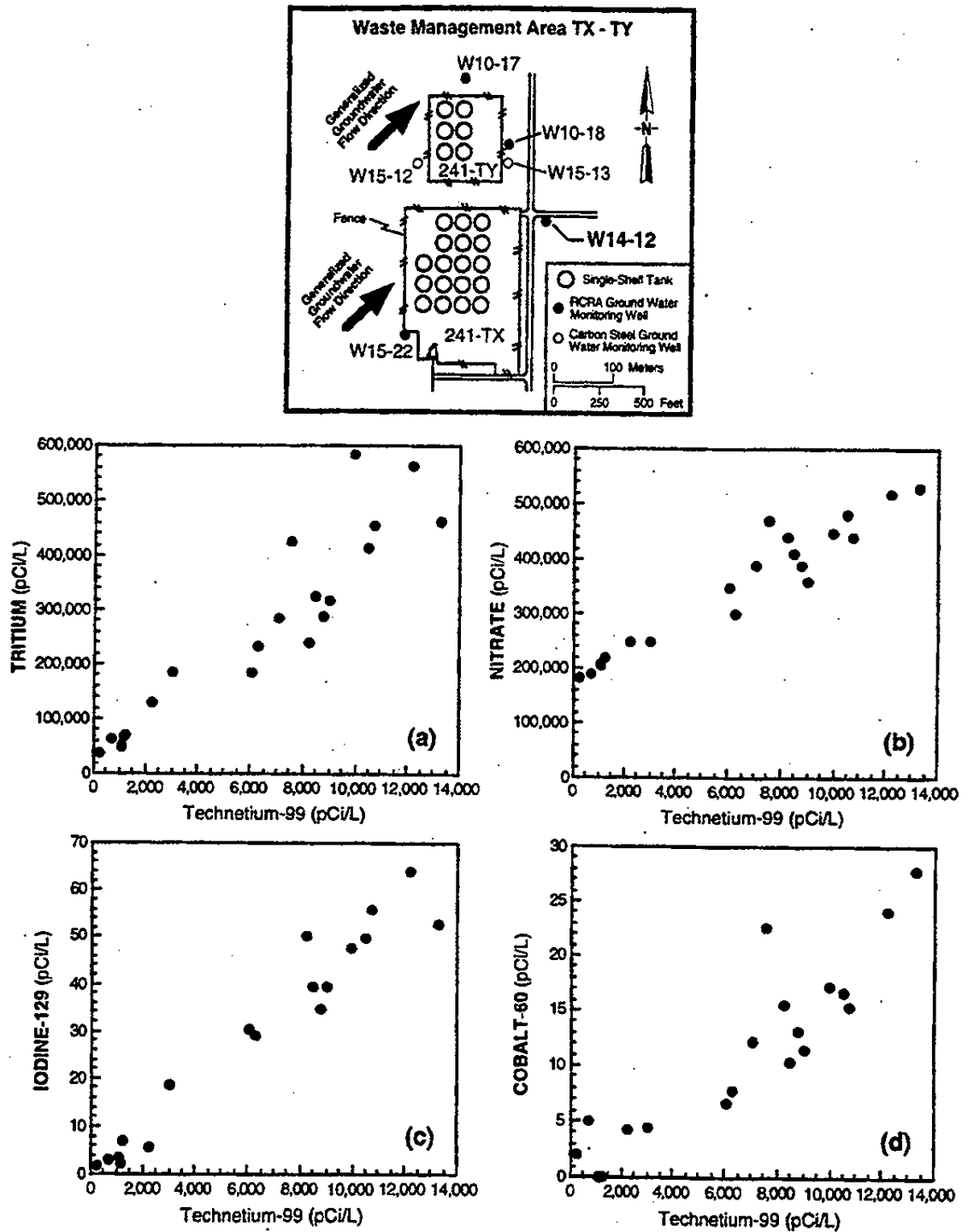
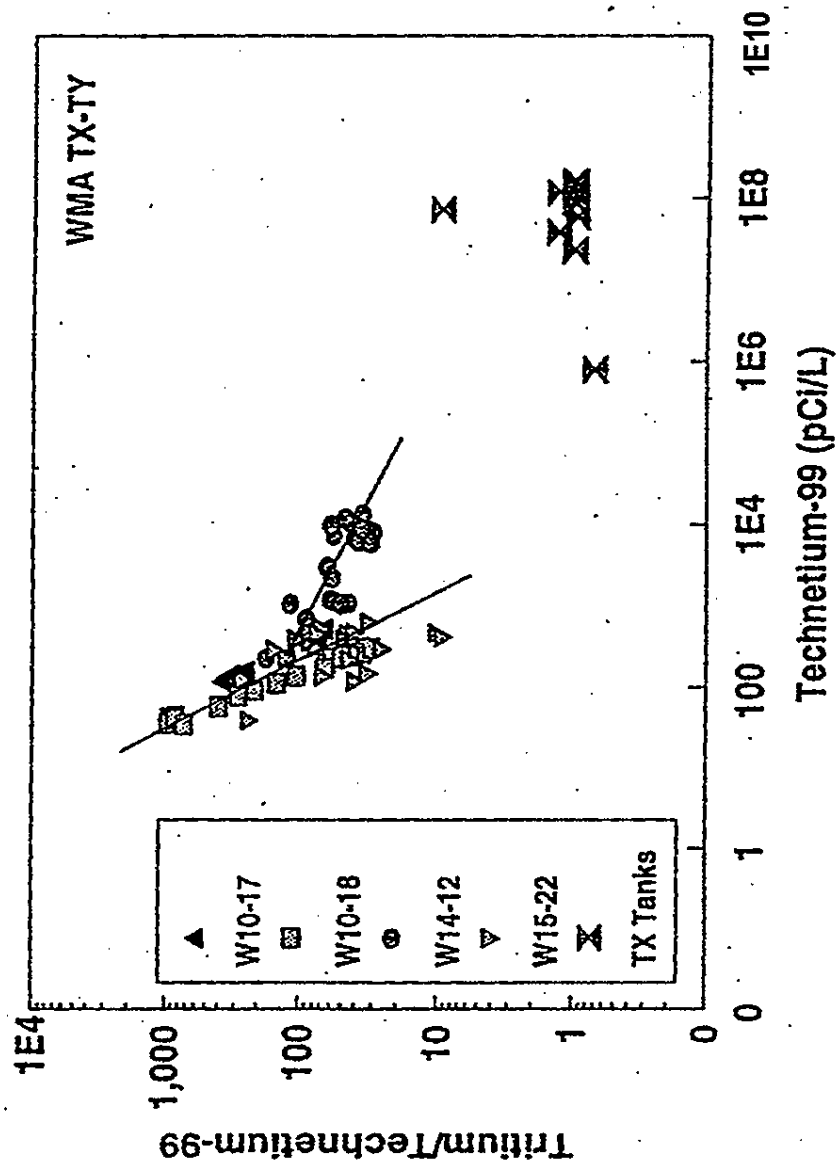


Figure 3-15. Plot of Tritium/ ^{99}Tc versus ^{99}Tc for Wells at Waste Management Area TX-TY (after Hodges 1998). (Well 299-W15-22 is the upgradient well.) (See Figure 3-11 for well locations.) [Tank Data from Agnew (1997).]



3.4.3 B-BX-BY Tank Farms

The groundwater monitoring network for the B-BX-BY tank farms is shown in Figure 3-16. In general, the groundwater flow direction beneath the B-BX-BY tank farms is toward the west. The water table elevation is approximately 122.4 m amsl and has declined about 1 m since 1990 (Figure 3-17). The water table elevations indicate an extremely flat gradient of about 0.0008. However, the groundwater velocities are high (ranging from 0.04 m/d to 0.08 m/d) because the hydraulic conductivity of the saturated Hanford formation is as high as 97.5 m/d.

Regional ^{129}I and tritium plumes extend beneath the tank farms in the 200 East Area. Locally, elevated levels of ^{99}Tc (Figure 3-18) have been observed in well 299-E33-41 (Figure 3-18) as of late 1996. This rise has been attributed to a potential tank leak at the BX Tank Farm. The biggest known leak, 265 kL of liquid, occurred at tank BX-102 during 1971.

Although Narbutovskih (1998) concluded that recent trends of ^{99}Tc and nitrate in other downgradient wells, including well 299-E33-32, may be caused by tank-related sources, no mobile cocontaminant analysis has been performed to discern contributions from other sources, as was done in other studies (Johnson and Chou 1998, Hodges 1998). Johnson and Chou (1998) used the observed technetium-uranium and ^3H -technetium ratios in the groundwater in their source-term evaluation (cribs versus tanks) for the S-SX tank farm.

High-density waste is an additional potential source of contamination beneath the BY-BX farms (Kasza 1993, Smith 1980). Kasza (1993) notes that high-density tributyl phosphate (TBP) supernatant liquid derived from ferrocyanide scavenging was released to the BY cribs, north of the B-BX-BY tank farms. Because of the supernatant liquid's density, the plume can be expected to sink through the aquifer to the lower confining layer (basalts) where it will flow south along the dip direction toward the tank farms. Further, the contaminants may seep into the fractured basalt layer, then later be released from the fractures, serving as a continuing source of contamination.

3.5 POTENTIAL FOR CROSS-CONTAMINATION DURING DRILLING

All subsurface samples collected with any well drilling technique are potentially compromised by cross-contamination. Contamination can be carried down as tools are moved down in the borehole. Drilling tools often carry contaminated material upward as the tools are operated or retracted from the bore. As discussed in Section 3.6.2, drag-down of contamination was apparent in borehole 41-09-39 during construction and extension, even though considerable effort was made in all instances to minimize its occurrence. Thus, care is required in evaluating data from analyses of core samples, particularly in cases where low contamination levels are reported such as the plutonium, strontium, and americium found in the Plio-Pleistocene layer (see Sections 3.2.5.1 and 3.6.1) in the 1993 tank T-106 investigation (Freeman-Pollard et al. 1994).

Figure 3-16. Monitoring Well Network for Waste Management Areas A-B-BX-BY Single-Shell Tank Farms (after Hartman and Dresel 1997).

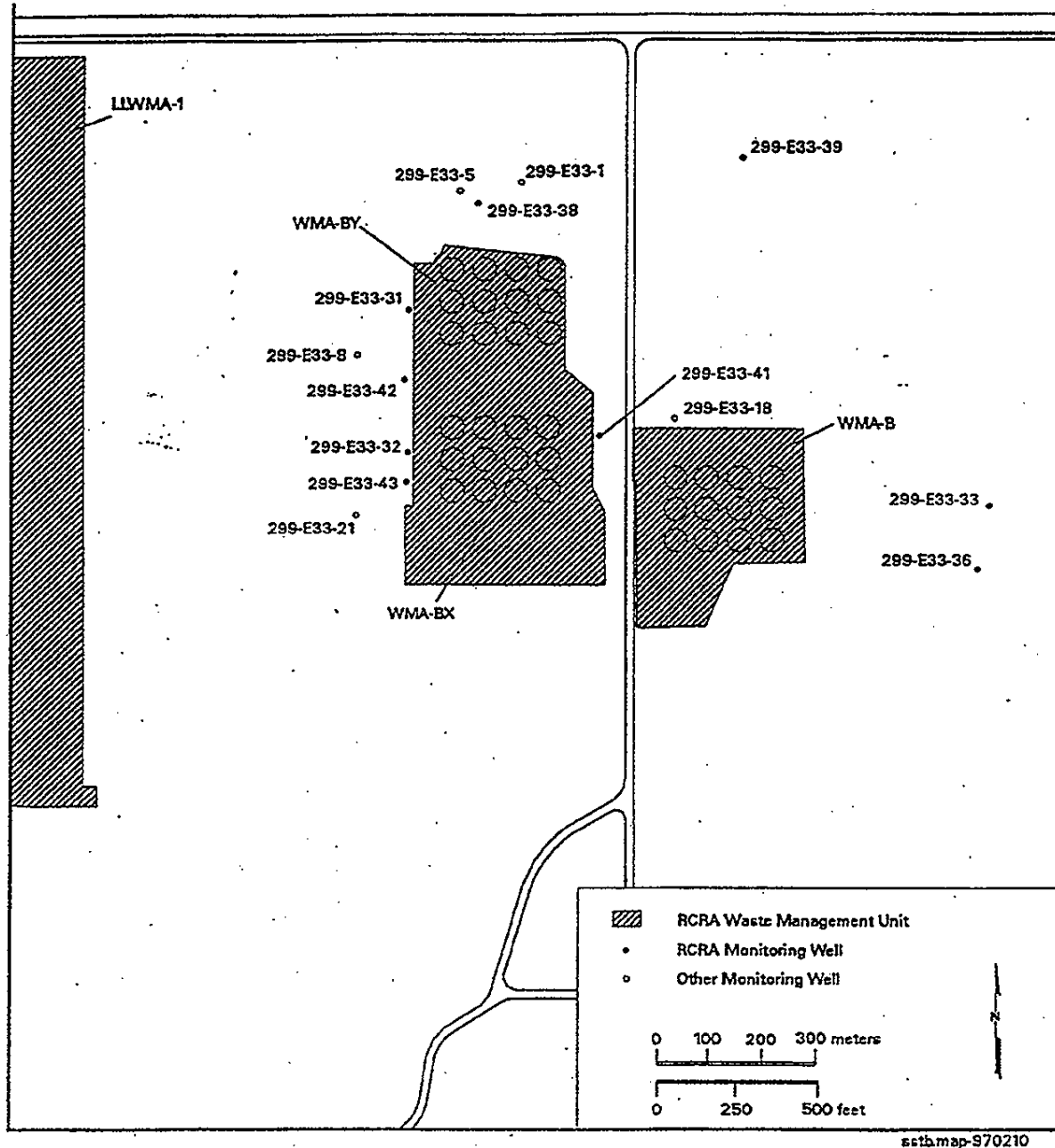


Figure 3-17. Water-Table Elevations in Wells Monitoring Waste Management Areas B-BX-BY Single-Shell Tank Farms (after Hartman and Dresel 1998).

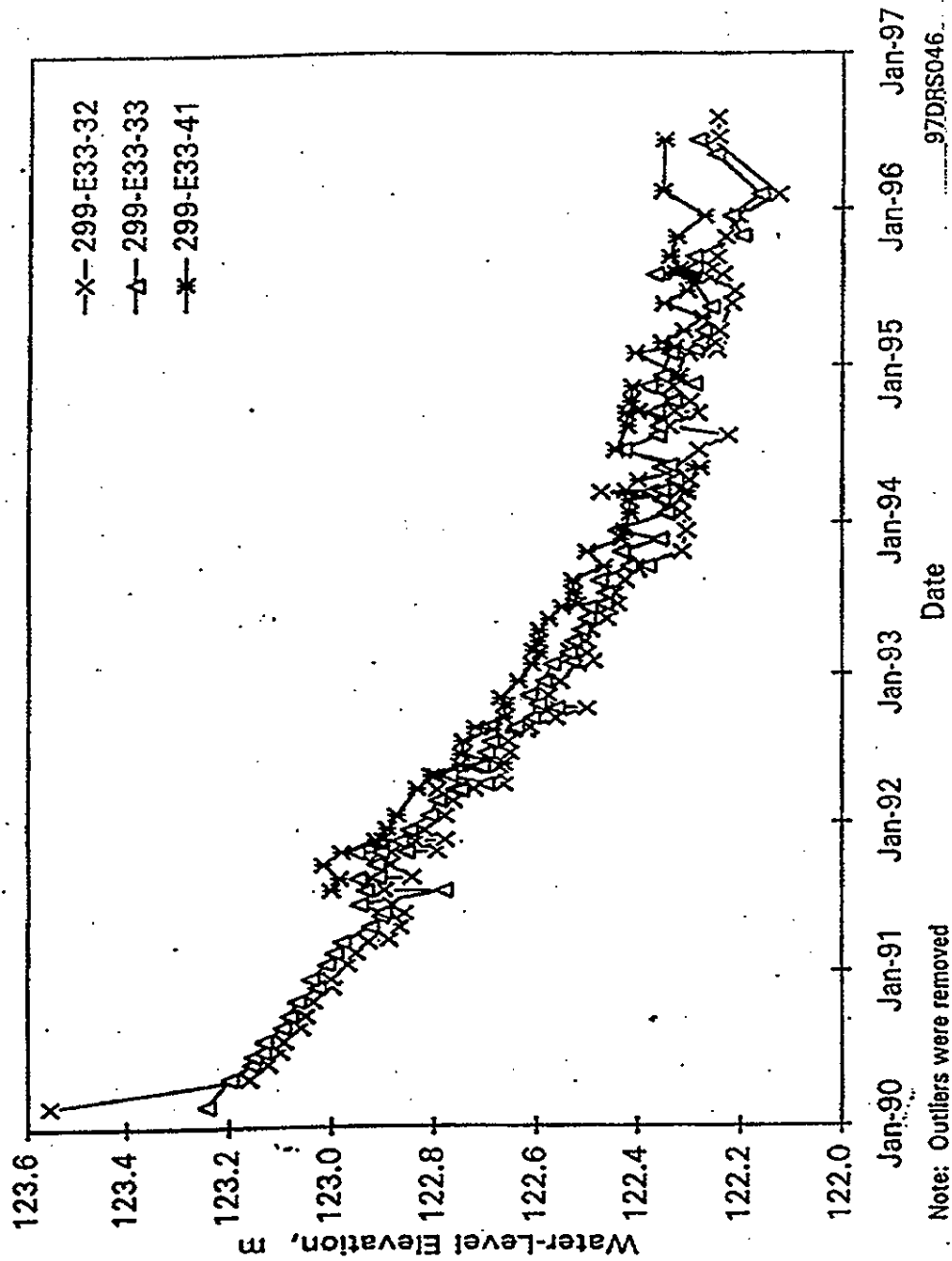
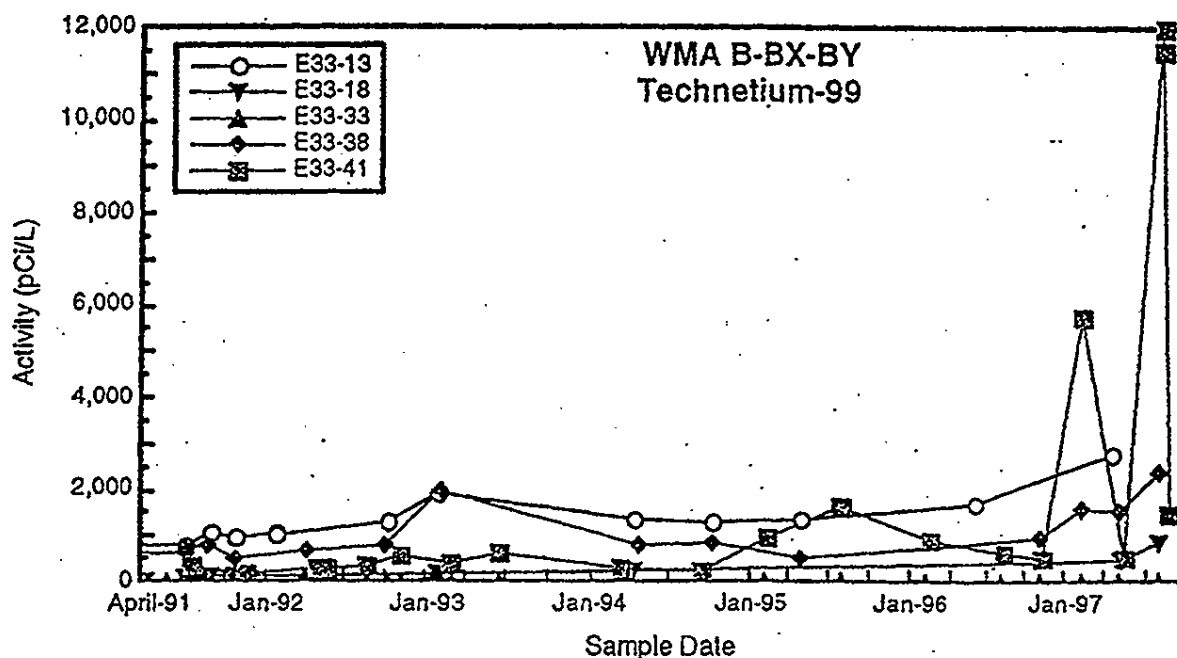


Figure 3-18. Trend Plot of Technetium-99 for Wells 299-E33-13, 299-E33-18, 299-E33-33, 299-E33-38, and 299-E33-41. See Figure 3-16 for Well Locations (after Narbutovskih 1998).



3.6 ANALYSIS OF SOIL SAMPLES CONTAMINATED FROM TANK LEAKS

3.6.1 Tank T-106 Soil Column Radionuclide Characterization

The tank T-106 leak has been one of the most studied tank leaks at the Hanford Site (ARH 1973, Routson et al. 1979). Most recently, Freeman-Pollard et al. (1994) have completed an extensive evaluation of the soil column contaminated by this leak. The type of radionuclide contamination most often evaluated in this zone has been high-energy gamma emitters, which are amenable to gamma logging measurements. While this information helps qualitatively map the extent of the leak event, it provides little information about other radionuclides that may have contaminated the soil. In particular, the distribution in the soil of other radionuclides likely to be mobile in the future and capable of contaminating the unconfined aquifer (chiefly ^{99}Tc and uranium isotopes, and perhaps ^{14}C and ^{129}I) needs to be determined.

Other than the extensive gamma measurements taken around the tank T-106 leak, the most comprehensive radionuclide contaminant characterization of soils near the leak source has been completed in borehole 299-W10-196 (Freeman-Pollard et al. 1994). The borehole is located just west of tank T-106 and was drilled through the zone of the highest gamma readings identified from previous measurements. Soil samples were collected at selected depths and analyzed for a

suite of radionuclides, common elements found in the supernatant liquid, and soil, water, pH, and organics. For this discussion, the characteristics of the radionuclide distribution are considered. Also, sodium, nitrate, and nitrite concentrations were determined. Their distributions in the soil column provide some indication of contaminant transport behavior.

This waste characterization effort is unique for tank-leak-contaminated soils at the Hanford Site because most environmentally mobile radionuclides were analyzed as a function of depth through the most highly contaminated part of the soil column. These include ^{99}Tc , ^{14}C , and uranium. The one long-lived mobile radionuclide not analyzed for was ^{129}I . In addition, several radionuclides not normally considered to be environmentally mobile but present in measurable concentrations were reported. These include ^{60}Co , $^{239,240}\text{Pu}$, ^{237}Np , ^{241}Am , ^{137}Cs , ^{90}Sr , and ^{154}Eu .

The split tube samples were taken from about 4 m (13 ft) below grade to about 55 m (180 ft) below grade. The bottom of tank T-106 is about 10 m to 11 m below grade. Samples were taken every 2 m to 3 m in this interval. Radionuclide concentration profiles display the following primary characteristics that reveal qualitative information about their mobility.

Cesium-137, ^{90}Sr , and ^{14}C were present in peak concentrations at or just below the tank bottom (about 10 m to 12 m) in the Hanford formation. Uranium had a peak concentration of $39\text{ }\mu\text{g/g}$ at 22 m; ^{99}Tc displayed a broad peak from 30 m to 40 m; ^{154}Eu peaked at about 22 m; and ^{60}Co showed no real peak. Sodium showed two peaks in the Hanford formation, one at the tank bottom and a slightly larger one at about 20 m.

The $^{239,240}\text{Pu}$, uranium, ^{90}Sr , and sodium displayed a secondary peak in the Plio-Pleistocene unit. Secondary peak concentrations are at much lower concentrations for these radionuclides (factors at 100 or more). The ^{237}Np , ^{241}Am , and ^{137}Cs were not detected in the Plio-Pleistocene unit and appear not to have reached this layer.

Based on these observations, some qualitative deductions can be made about the relative mobility of the various species. The key indicators are the relative depth of concentration peaks and the depth intervals over which the species are identified. The primary peaks occurring above the Plio-Pleistocene indicate that some sort of chemical reaction has occurred to fix a fraction of the radionuclide in place and/or retard its movement downward relative to movement of tank leak fluid toward the water table. Contaminants identified at greater depth obviously show less retardation of transport relative to tank leak fluid flow rates. Mapping of ruthenium distribution from work shortly after the leak (ARH 1973) provides a marker for the extent of the leak penetration into the soil column. Ruthenium is known to be highly mobile and should have been transported downward at essentially the same rate as the leaking tank liquid. The earlier data (ARH 1973) indicate that the initial leak volume quickly reached the Plio-Pleistocene layer about 30 m below the surface. The distribution of ruthenium suggests that the relatively lower permeability of the Plio-Pleistocene layer stopped the downward flow of the leak and forced it to move horizontally, at least temporarily. Later measurements showed ruthenium extended below the Plio-Pleistocene into the Ringold.

The concentration-versus-depth patterns suggest several broad levels of mobility. The least mobile species are those showing large peaks just below the tank bottom and detection only in the Hanford formation above the Plio-Pleistocene layer. One large peak with relatively little contamination below the peak indicates a relatively rapid and extensive reaction (e.g., sorption and/or precipitation) with the soil column soon after the leak occurred. The radionuclides in this group are ^{137}Cs , ^{237}Np , and ^{14}C .

The next most mobile species are found lower in the soil column and exhibit a broader high concentration band that begins at and extends further below the tank bottom. Also, these radionuclides are present at lower concentrations down to the Plio-Pleistocene layer where a much smaller secondary peak occurs (approximately 1000 Ci less than the maximum activity). These radionuclides include ^{90}Sr and $^{239, 240}\text{Pu}$, uranium, and sodium.

Finally, the most mobile radionuclides show similar concentrations throughout the Hanford formation, through the Plio-Pleistocene, and into the Ringold Formation. The radionuclides and chemicals in this group are ^{99}Tc , ^{60}Co , nitrite, and nitrate. All radionuclides except ^{99}Tc and ^{60}Co have been retarded relative to the downward movement of tank leak fluid leak water, as shown by the extent of the initial ruthenium plume.

Similar concentration distribution patterns do not necessarily indicate that the same mechanisms are controlling mobility for the grouped radionuclides. Known chemical tendencies of elemental behavior under natural conditions, chemical properties of tank liquors that influence radionuclide behavior, and the physical properties of the soil materials all potentially contribute to the observed distributions.

In the first group (^{137}Cs , ^{237}Np , and ^{14}C), the radionuclides are not expected to behave similarly under normal conditions. The ^{137}Cs is expected to sorb strongly under normal conditions and appears to do so in this situation when compared to other radionuclides. However, ^{137}Cs 's mobility appears to be substantially enhanced relative to the normal soil conditions. Under normal conditions (minimal hydraulic driving force and unaltered groundwater chemistry), ^{137}Cs would be expected to penetrate no more than a few inches. This leads to the conclusion that a factor or set of factors unique to the tank leak environment has substantially enhanced ^{137}Cs 's mobility.

One likely factor is the amount of sodium present. The tank liquid contained large concentrations of sodium, and experimental data (Ames and Rai 1978) demonstrate a substantial reduction in ^{137}Cs sorption in the presence of high concentrations of sodium, which competes with cesium for sorption sites on soil minerals. A quantitative estimate of enhanced mobility cannot be determined without additional information, such as a release and transport modeling analysis or laboratory tests that measure ^{137}Cs under simulated conditions (^{137}Cs dissolved in simulated tank liquids reacted with Hanford formation soil). Interestingly, the pattern of cesium distribution in this soil column is similar to the soil column contaminated by the tank SX-108 leak. The main difference is that the ^{137}Cs concentration peak is deeper beneath tank SX-108.

Normally, ^{237}Np has a K_d value in the range of 3 mL/g to 20 mL/g. In these soils, clearly some sorbing process has occurred. The sorptivity may tend toward the lower end, perhaps

because of the presence of complexing agents. The potential for ^{237}Np interacting with these complexing agents is not well known. What is known in this instance is that ^{237}Np was, at least temporarily less mobile than americium and plutonium in these soils. Again, without additional information, quantitative estimates of a retardation factor cannot be generated.

The data for the ^{14}C plume under tank T-106, the first of their kind at the Hanford Site, are very interesting. Typically, in modeling analyses, ^{14}C is modeled as highly mobile ($K_d = 0 \text{ mL/g}$) because it forms neutral or anionic species. At the same time, ^{14}C 's behavior is known to be complex; it can undergo a variety of chemical reactions. These include isotopic substitution with naturally occurring carbon, which is a constituent of at least one ubiquitous soil phase (calcite, CaCO_3) in Hanford Site soils, dissolution into a gaseous state, or precipitation in a solid phase as tank liquid interacts with the soil column phases. The data clearly indicate that ^{14}C is one of the most immobile radionuclides in the tank liquid, perhaps indicating that precipitation reactions substantially control ^{14}C mobility.

Americium and plutonium mobility are clearly enhanced relative to normal soil-groundwater conditions. The mobility of these elements may have been caused by the formation of aqueous complexes with organic complexants initially present in the tank liquid. Another option is that colloids may have formed that could have been transmitted with the tank liquid, at least temporarily. A third option is that these isotopes may have moved with the leak water for a short period because the leak water flow rate exceeded the kinetics of the americium and plutonium sorption reactions. Once the flow rate subsided, sorption reaction kinetics would have caught up and fixed part of the contaminants. Under normal conditions, americium and plutonium would have remained close to the leak source and the distribution pattern would have indicated less mobility than ^{237}Np . This is the opposite of what was observed.

The mechanism that caused the secondary plutonium peak in the Plio-Pleistocene is unclear. The simplest explanation is that a fraction of the plutonium activity was sufficiently mobile to move with the tank fluid and, because larger quantities of tank fluid collected in the fine-grained Plio-Pleistocene layer than in coarser grained material, a relative increase in concentration was measured. The moisture content profiles show an increase in the Plio-Pleistocene. It is important to keep in mind that this apparent greater degree of mobility is restricted to a small fraction of the contaminant activity.

The ^{90}Sr and sodium show nearly identical patterns with a secondary peak in the Plio-Pleistocene layer. The ^{90}Sr is likely to have sorbed less effectively than expected because it had to compete for ion exchange sites with other alkaline earth elements present in the initial tank liquor, particularly calcium. As with the plutonium secondary spike, the simplest explanation is that strontium and sodium in the Plio-Pleistocene moved with migrating tank leak fluid, which concentrated in that layer because of its fine-grained characteristics.

Uranium will behave differently. Precipitation of uranium-bearing phases is expected and dissolved uranium (controlled by the solubility of the precipitate) is expected to be rather mobile. The occurrence of concentration peaks is consistent with the occurrence of precipitation reactions which are, in turn, sensitive to changes in liquid chemistry, particularly pH. The exact history of

liquid chemistry as a function of depth is not known. Single or multiple events may have occurred at locations of high uranium concentration that were conducive to uranium precipitation. On the other hand, detection of uranium at the bottom of the Plio-Pleistocene unit demonstrates the high mobility of dissolved uranium.

Finally, the radionuclides expected to be essentially unretarded relative to leak water flow show a characteristic pattern of a generally broad peak whose maximum concentration occurs in the Ringold Formation just below the Plio-Pleistocene unit. The ^{99}Tc and nitrite and nitrate plumes are essentially identical. The ^{60}Co does not really display a distinct peak in the Ringold Formation, but its half life is sufficiently short (5.6 years) that relative decay may have eliminated the peak distribution.

The radionuclide distributions discovered by these recent studies and their mobility implications are not expected to reliably indicate future transport because physical and chemical conditions imposed by the leak event have dissipated or continue to dissipate. Fortunately, most temporary conditions appear to have enhanced radionuclide mobility and a return to pre-Hanford Site operations soil-water chemistry conditions should reduce mobility in the future (e.g., when considering transport through the lower portion of the vadose zone). The leak-related anomalous conditions with the greatest effect on transport of contaminants from the tank T-106 leak appear to be an initial rapid flux of tank liquid into the soil column; the presence of organics complexing with americium, plutonium, and cobalt; and the presence of high concentrations of alkaline elements; successfully competing with ^{137}Cs and ^{90}Sr for sorption sites. Organic complexes may break down in the soil column and high sodium concentrations in water cannot be sustained. The ^{99}Tc has been largely unaffected chemically and future discharge of ^{99}Tc into groundwater will occur according to the hydraulic forces imposed by current conditions and the current distribution of ^{99}Tc in the soil column.

3.6.2 Extension of Borehole 41-09-39, 241-SX Tank Farm

Borehole 41-09-39 was initially drilled in 1996 to a depth of 39.6 m (130 ft) in response to the determination that ^{137}Cs might reside in the soil column at depths greater than 30 m (100 ft). The borehole was drilled to ascertain whether the contamination was an artifact of an adjacent unsealed borehole or disseminated in the formation. Geophysical logging of borehole 41-09-39 confirmed that dissemination within the formation was probable, and that contamination was still present at a depth of 131.5 ft.

Concern was raised that if relatively immobile ^{137}Cs was present at that depth, more mobile, long-lived tank waste constituents such as ^{99}Tc might well be at or near the water table at about 64.3 m (211 ft) deep. In response to a recommendation from an expert panel brought together to address these early findings (RL 1997), borehole 41-09-39 was extended to groundwater and samples of both sediments and groundwater were collected for laboratory analyses of tank waste components (Myers et al. 1998).

The closed-bottom casing tip of the initial borehole was removed by milling with a core drill and the borehole was extended by sequentially driving a split-spoon sampler into the formation ahead of the drill casing, then cleaning the bore to the depth sampled, driving the drill casing to that depth, and finally cleaning out the drill casing again. This process was repeated to collect another sample. Straightness of the initial pipe, and its 6-in. inside diameter restricted the size of the extended borehole to 4.5 in. inside diameter. The cable-tool drilling method was used to advance the borehole. The bore was first advanced using a flush-threaded casing shoe to restrict hole diameter and prevent any contamination outside the bore from being dragged down the hole as it was advanced. Geologic conditions caused excessive friction against the drill pipe effectively stopping progress. To remedy the situation, the drill casing was removed from the bore and the drill shoe replaced with an oversized one that under-reamed the bore, reducing friction and allowing the casing to be advanced. The under-reaming casing shoe created a small annular space that may have contributed to drag down of contamination.

Samples were collected in a near-continuous manner. Samples were not collected when geologic conditions required that a hard tool be used; and that use rendered the returns unrepresentative. All drill cores returned to the surface were preserved for potential analysis. All cores were screened for gamma-emitting radionuclides and moisture content. In addition, each core section was described geologically. Samples from seven selected locations within the borehole were analyzed for radionuclides, chemical constituents, cation exchange capacity, and particle size distribution.

Frequent geophysical logging of the borehole was used to indicate the occurrence of drag down and provide additional data used in selecting the seven locations for complete analysis. Gamma logging techniques were used throughout the drilling effort. Initially, the gamma tools were operated in a total (gross) gamma mode, but as drilling proceeded the logging mode was changed to the spectral gamma mode to indicate what gamma emitters were present and at what concentration they were being carried along with the casing or drilling activities. On completion of the borehole, a neutron moisture gauge log was run. Geophysical logging indicated that some contaminated material was following the casing as it was advanced. Indicated contaminant levels were low.

Screening analyses of the samples showed that the upper sample sleeves from the split-spoon sampler often exhibited low levels of contamination, but no contamination was detectable in the lower sleeves. The regularity of this occurrence resulted in its being interpreted as cross contamination, either from material carried along the outside of the casing or from material smeared along the inside of the casing that was deposited as the drill tools and samplers were inserted or extracted from the bore. Samples from the upper split-spoon sleeves were excluded from analysis when evidence of such possible cross contamination was found.

Analysis of the seven composited samples from this borehole show that tank waste constituents are predominantly held by the sediments within or above the Plio-Pleistocene soil horizon. Nonradiological constituents (sodium, calcium, and nitrate) point to the leading edge of tank waste components being at a depth of about 47 m (135 ft). This leading edge may result

from natural processes or from drag-down; this study was unable to determine which is most likely.

Analyses for ^{137}Cs , the radionuclide originally recognized as being deeper than anticipated in the vadose zone, were conducted on all samples via gamma energy analysis. Cesium-137 activity in the soils was highest associated with the Plio-Pleistocene sediments at 40 m (131 ft). Activity dropped off rapidly and was at or below detection levels from 48.8 m (160 ft) to the water table at 64.3 m (211 ft).

Technetium-99, the most mobile of the long-lived radionuclides found in tank waste, was sporadically distributed, with most occurrences above the minimum detection level being above the caliche-rich horizon. A single deep occurrence was noted at 56.3 m (184.6 ft); this is the location postulated to be the highest level reached by groundwater during operation of the U Pond. The ^{99}Tc could have migrated horizontally from disposal facilities outside the tank farm boundaries to the sediment extracted. If the technetium source was the SX tanks, we would have expected to see near continual detection throughout the shallower sediments.

Desorption distribution coefficient (K_d) tests were run on sediment samples for both ^{137}Cs and ^{99}Tc . These tests showed that ^{137}Cs is strongly bound to the fine-grained sediments. The tests for ^{99}Tc showed positive values for the K_d , but significant uncertainty was associated with those values.

Groundwater samples were collected from 3 m, 0.6 m, and 0.02 m (10 ft, 2 ft, and 1 in.) below the water table. Analyses of these samples showed ^{99}Tc and tritium concentration ratios indicative of upgradient sources. Analyses for chromium were consistently below the method detection limit. These analyses indicate that groundwater contamination at this location is caused by non-tank-farm sources and serve to narrow the possible sources of tank waste constituents found in downgradient monitoring wells.

4.0 CONCEPTUAL MODEL FOR MIGRATION OF TANK WASTE THROUGH THE VADOSE ZONE

The information documented in Chapters 2 and 3 and the appendices clearly indicates that leaks of fluids processed through the tank farm systems into the vadose zone are complex events affected by many physical and chemical processes and conditions. Based on this extensive data compilation, we have developed a conceptual model to describe our understanding of the physical and chemical processes that control the migration of tank waste through the vadose zone.

Vadose zone contamination in each tank farm is, to a certain extent, unique. Even so, a practical and effective means is needed for evaluating potential risk from contaminants currently residing in the vadose zone under the tank farms, from future contamination that may result from tank waste removal operations, and from any residual waste that may remain in the tanks. Without such an approach, waste management decisions cannot be made in a timely and consistent fashion. Developing a conceptual model is an integral part of such an approach.

A conceptual model is used in several ways. First, it provides an organized description of waste migration that can be evaluated as additional information is collected. Additional information will enhance confidence in the validity of the model, disprove aspects of the model, or induce generation of a new or refined model.

Second, it provides a framework for the risk assessment approach that can be applied to each major contaminated region within the vadose zone. The conceptual model identifies processes and conditions that apparently are common to all leak events. The described processes are consistent with the available database, widely accepted understanding of fundamental physical and chemical processes, and previous modeling results. The processes described are expected to be the most significant drivers of contaminant migration. Because of the variety of specific site conditions and events, the conceptual model is generalized. For illustration, some site-specific examples of potentially significant processes or conditions are briefly identified.

Third, it guides the application of a numerical flow and transport computer codes to project contaminant migration from the source (in this case the contaminated vadose zone). The codes may be used to model previous leak events leading to present conditions and to estimate future distributions of contaminants. The conceptual model guides formulation of input parameters needed to quantify migration events. Remember that the numerical codes themselves are largely limited to approximating conditions that are simplified or generalized when compared to the heterogeneity of natural and disturbed hydrogeologic conditions. This is inevitable because of limitations on data collection and computing capability. Despite these limitations, numerical modeling tools are routinely used to make waste management decisions.

Fourth, developing a conceptual model combined with previous modeling results at the Hanford Site involving contaminant migration through the vadose zone (e.g., Wood et al. 1995, Wood et al. 1996, Mann et al. 1998, and Kincaid et al. 1998) aids in prioritizing future data collection and analyses. This process and recommendations are provided in Chapter 6.

4.1 ORGANIZATION OF THE CONCEPTUAL MODEL

The conceptual model for understanding how tank waste migrates through the vadose zone is defined as a series of chronological events roughly distinguished by changes in the environmental conditions that control radionuclide migration. These events overlap and evolve, but we separated them here for convenience. The four events are as follows:

- Initial environmental conditions imposed by installation of the tanks
- Loss of tank waste fluids into the soil column
- Further migration of tank contaminants after the initial leak forces have been spent
- Capping of the tank farms to eliminate the enhanced infiltration caused by their construction.

The most important factors determining how contaminants are distributed within the vadose zone include geology, hydrology, leak volume, and tank waste chemistry. The databases summarized in Appendices A (geology), B (hydrology), and C (geochemistry), and those in RL (1997), Serne et al. (1998), Myers et al. (1998), Freeman-Pollard et al. (1994), Ward et al. (1997), Narbutovskih (1998), Hodges (1998), and Johnson and Chou (1998) are the primary information sources used to develop the generalized conceptual model. Other conceptual model discussions, found in RL (1997), Ward et al. (1997), Narbutovskih (1998), and Johnson and Chou (1998), have been incorporated into this discussion. More detailed and site-specific versions of the conceptual model are expected as each major site is more thoroughly investigated.

4.2 INITIAL CONDITIONS

To construct the tanks, surface soils were excavated down to about 21 m (70 ft) and the tanks were installed, covered with excavated soil, and topped with a thin layer of gravel. These activities changed the hydrologic properties of the soil. Tank farm surface gravels have been kept free of vegetation. These bare gravel surfaces enhanced the annual net infiltration of meteoric water. Infiltration was further enhanced in tank farms because of the umbrella effect created by the 23 m-diameter buried tank domes. Water, shed from the tank domes, flows down the tank walls into underlying coarse sediments. Sediments adjacent to the tanks, while remaining unsaturated, probably attained higher moisture content than undisturbed soils. Also because of the umbrella effect, soils directly under the tanks are expected to be somewhat drier than the natural soil. However, other hydrologic properties (e.g., moisture retention and unsaturated hydraulic conductivity relationships) were not affected in the undisturbed soil. Variable water fluxes are therefore established in the tank farms. Geochemical properties were not substantially altered by tank installation.

4.3 TANK LEAK EVENTS

Once constructed, the tanks were used to store various waste products from processing plants. The combination of tank design and waste characteristics led some tanks to lose integrity and release liquids into the vadose zone. Historically, leaks were detected by measured drops in tank liquid levels and gamma logging with depth from dry wells placed around tanks. In a few cases, further characterization has been done. One example is the investigation of the tank T-106 leak (Section 3.6.1). Figures 4-1 through 4-3, taken from the initial investigative report of the tank T-106 leak, provide a reasonable picture of the plume produced by a tank leak. They track the concentration distributions of ^{137}Cs , ^{144}Ce , and ^{106}Ru , respectively. Figures 4-2 and 4-3 also show the waste plume from a near-surface leak from tank T-103 comingling with the plume from tank T-106. Comingling of plumes from different sources or multiple leaks from a single tank complicates understanding these plumes.

Distribution of the volume of leaked fluid was influenced by several factors including the following:

- **Leak Volume.** Leak volume is a significant hydraulic driver. Leakage continued until all available liquids were released or the leak hole was plugged. Leak rates also may have influenced liquid distribution in the underlying soil column, although the effect of leak rates on fluid distribution is not known.
- **Nature of Flow Pathways.** Leaks from tanks and tank-related sources are expected to move downward by advection. The layered nature of the sediments would cause some lateral spreading. A secondary mode of transport is preferential flow. Preferential flow can be via clastic dikes and in the form of fingering, funnel flow, and flow along unsealed annular spaces around drywells. (See Appendix B for details.)
- **Soil Hydrologic Properties and Geologic Heterogeneities.** As leaking fluid discharged into the underlying soil column, soil hydrologic properties, either natural or locally influenced by chemical interactions with the leaking fluid, controlled the fluid's movement. The distribution of the leak from tank T-106 suggests a strong lateral component in the distribution attributed to the intrinsic soil properties and heterogeneities in the soils (e.g., the occurrence of horizontal lenses of silt-rich materials dispersed in sand beds). For the 200 West Area tank leaks (i.e., tanks T-106 and SX-108), the Plio-Pleistocene layer appears to have acted as a partial low-permeability barrier limiting further downward movement of the leaked fluid. Conversely, Narbutovskih (1998) suggests that leaks from the B-BX-BY tank farm in the 200 East Area may have migrated more consistently in the vertical direction because of the lack of lateral, fine-grained units.
- **Other Leaks.** In any given contamination zone, more than one leak source could have released fluids simultaneously or over time. Other sources may include more than one tank, leaks in transfer lines, diversion boxes, and catch tanks between the

Figure 4-1. Concentration Distribution of Cesium-137 (from ARH 1973).

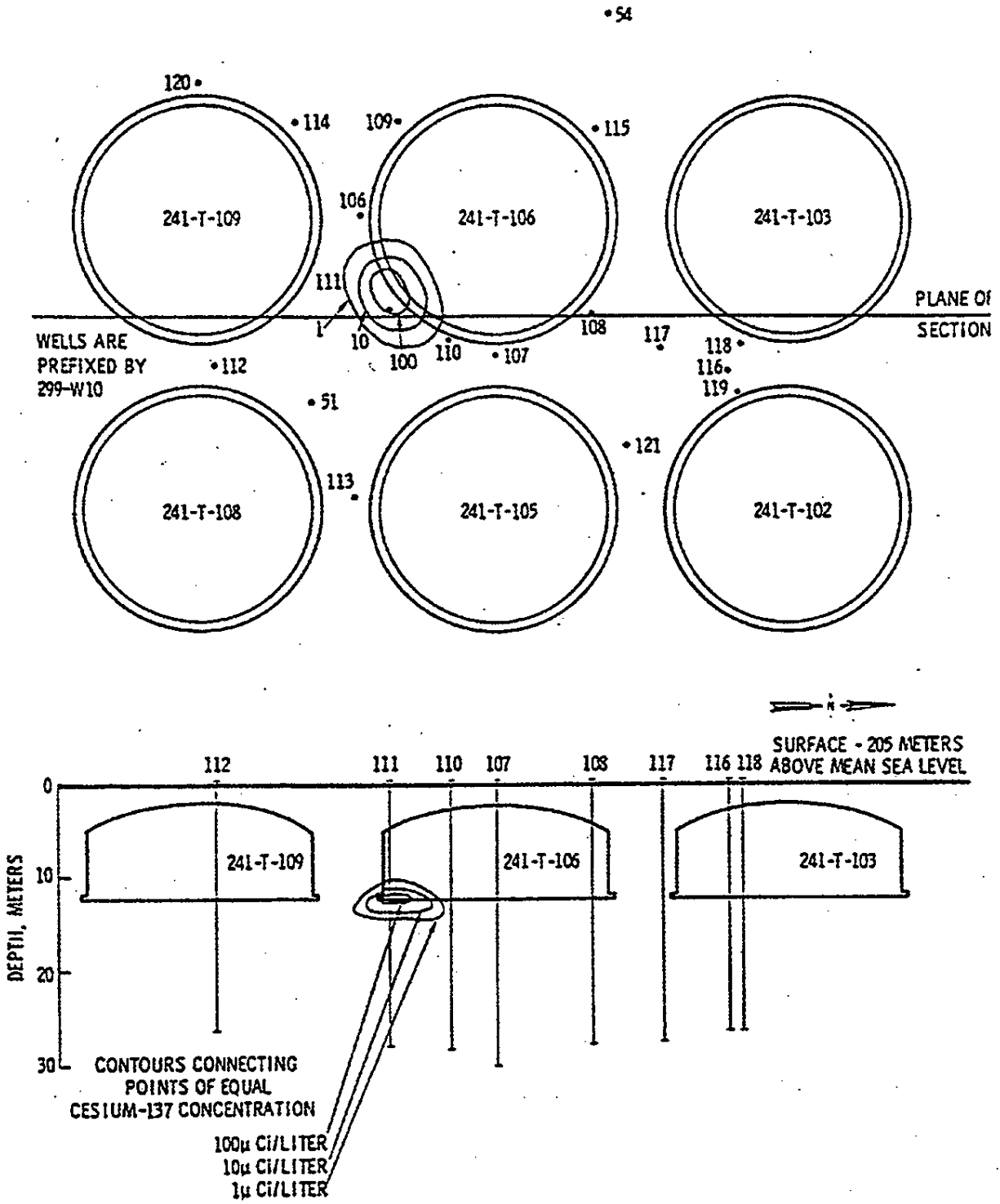


Figure 4-2. Concentration Distribution of Cerium-144 (from ARH 1973).

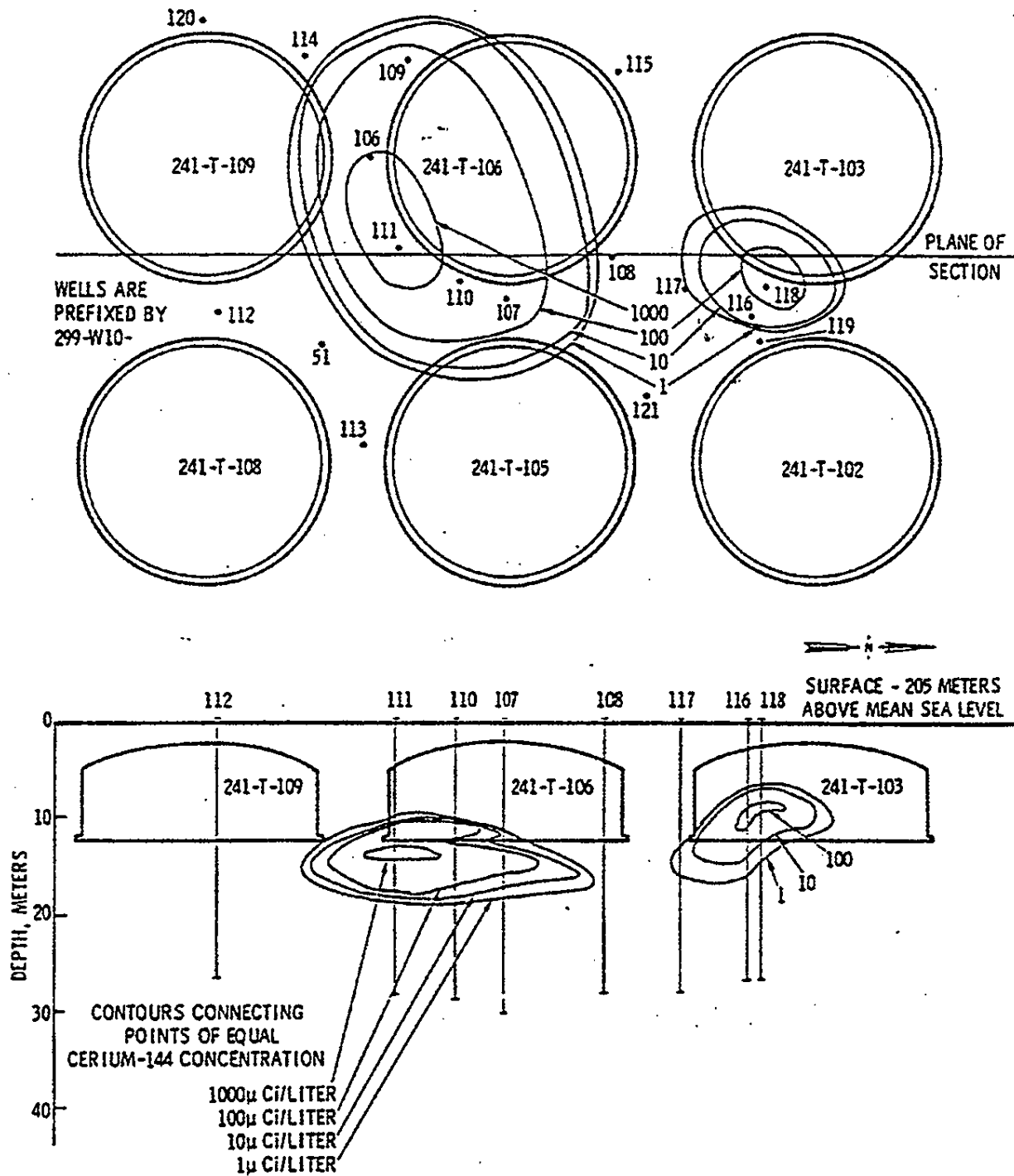
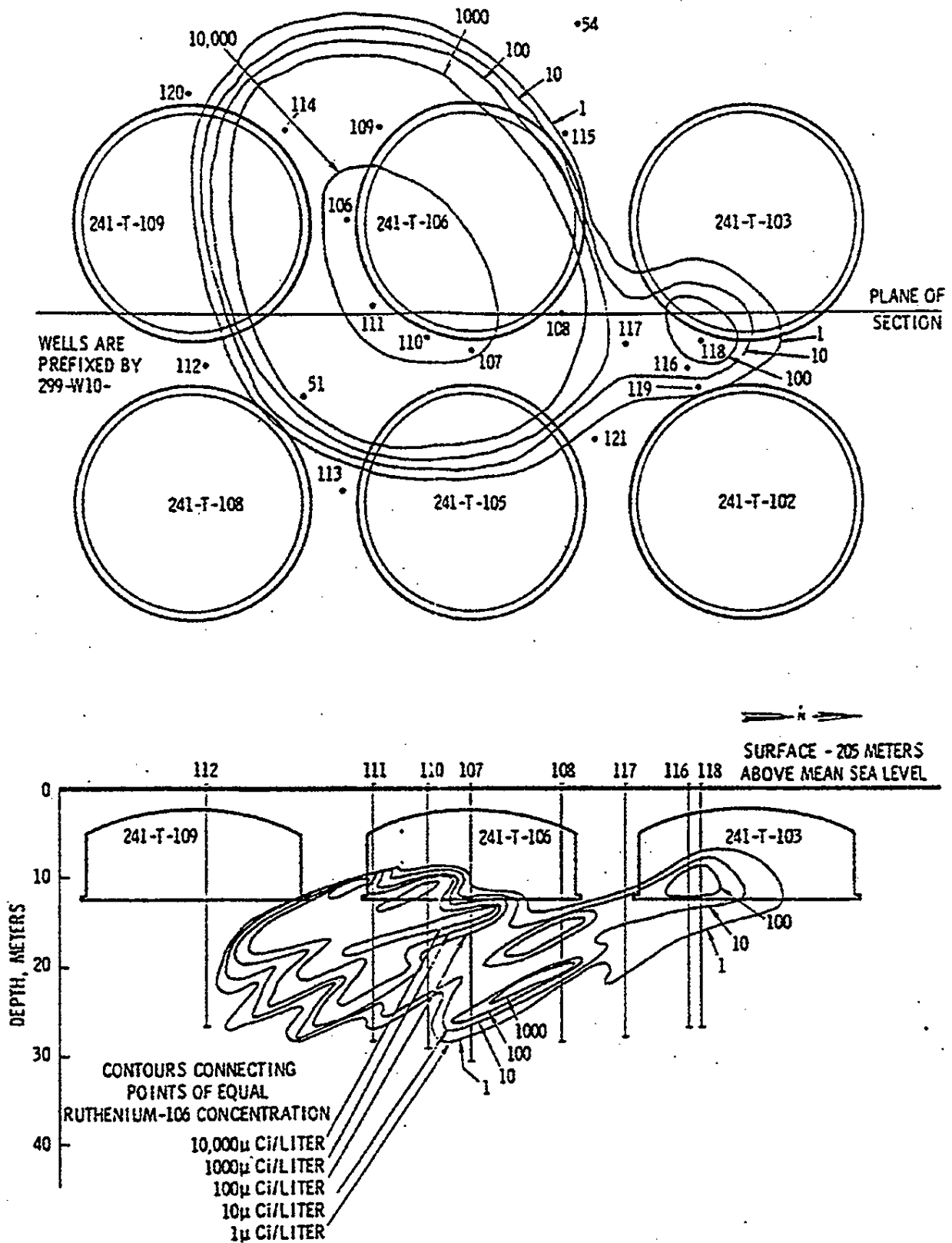


Figure 4-3. Concentration Distribution of Ruthenium-106 (from ARH 1973).



primary storage tanks and cribs into which deliberate tank overfills were discharged. The consequences of releases from other sources would be the introduction of additional fluids and contaminants in the same area and would frequently be indistinguishable from a tank leak. Narbutovskih (1998) suggests that subsequent leak events also could remobilize contaminants leached into the soil column from previous leak events.

Migration of contaminants in the leaking fluid also was influenced by waste chemical reactivity with the soils. In most cases, primarily because of elevated pH and high total dissolved solids, fluid chemistry was substantially different from natural water and, under natural soil conditions, could have intrinsically changed the reactivity of some radionuclides. For example, high sodium content successfully competes for sorption sites with ^{137}Cs , thereby escalating ^{137}Cs migration. Ward et al (1997) examined ^{137}Cs migration data from leaks from tanks SX-108 and SX-115. A key observation was the rapid vertical penetration of ^{137}Cs soon after the leak. This could only have occurred if ^{137}Cs was chemically unreactive as the leaking fluid migrated through the upper portion of the vadose zone.

The different fluid chemistry also could have influenced radionuclide reactivity by reacting with the soils. For example, high pH and aluminum content may cause dissolution of existing soil phases followed by reprecipitation of other phases, chemically or physically trapping radionuclides in the process. (See Serne et al. (1998) for a discussion of laboratory simulation of this process).

The influence of chemical changes to radionuclide migration caused by the leak fluid was a function of the chemical nature of a particular radioisotope, the location in the soil column, and time. In their modeling efforts, Ward et al. (1997) determined that ^{137}Cs migration history was reproduced by assuming a variable K_d value for ^{137}Cs , mimicking gradual buffering of tank fluid chemistry over time, with ^{137}Cs sorption increasing as sodium content in solution decreased. For naturally mobile radionuclides, primarily ^{99}Tc , chemical changes were less likely to influence their migration. Chemically perturbed zones became less significant with increasing distance from the leak source because the amount of available tank liquid was limited and the buffering capacity of the soil ultimately overcomes the initial effects of tank liquid chemistry. Elevated pH and high inorganic concentrations are reduced over distance. Changes in radionuclide mobility induced by tank liquid chemistry also may be reversed over time as buffering reactions occur.

4.4 POST-LEAK MIGRATION (PRECLOSURE TANK PHASE)

Having achieved some distribution in the soil column as a function of many factors, further distribution of leaked fluid and radionuclides will be controlled primarily by prevailing hydrologic and geochemical conditions. The moisture regime established by initial tank construction will provide the hydraulic driver. Abnormal geochemical conditions imposed by interactions between soils, natural water, and tank fluids will have largely dissipated as the large buffering capacity of the vadose zone system eliminates anomalous conditions (e.g., higher pH and high concentrations of inorganic species). Radionuclide reactivity will be similar to that observed under natural conditions. Essentially, only known mobile radionuclides will be able to migrate over significant distances.

If retrieval operations result in large volumes of liquid being discharged into the contaminated soil column, a temporary hydraulic driver will be created that simulates the previous tank leaks to some extent. Fluids leaked during retrieval operations are expected to be caustic and rich in sodium, but may not be as concentrated in salts as supernatant liquids, depending on the constraints and criteria developed by retrieval operations for waste transfer (e.g., specific gravity and total dissolved solids). Any leakage that would occur during retrieval would be expected to have a finite duration and limited volume. Multiple leakage events from adjacent tanks during retrieval operations could have a combined effect on a specific contaminant volume from a previous leak. Each of these multiple events would have a finite volume and duration, unlike natural recharge processes, which are more continuous. If leaks occur, they are expected to be caused in one of two ways. The first is reopening old leaks near the tank bases caused by hydraulic forces at dissolution attributed to liquid-based removal methods; the second is spills at the surface. Also, the occurrence of new leaks in tanks currently considered sound caused by ongoing corrosion coupled with retrieval actions cannot be discounted. The impact of retrieval leaks on existing contaminant volumes is expected to be primarily remobilization and separation of contaminants similar to those described for initial leaks of supernatant liquid.

4.5 POST-LEAK MIGRATION (POST-CLOSURE PHASE)

Multiple post-closure conditions are plausible. This conceptual model assumes that at least some infiltration-controlling cap will be placed over the tank farms and no additional tank liquids will be available for release. This will return the hydrologic system to pre-Hanford operation conditions. Infiltration rates will be substantially reduced and heterogeneous zones of water flux will be eliminated. Assuming no additional leakage of tank fluids, geochemical conditions will be similar to natural conditions. For mobile radionuclides remaining in the vadose zone, flux into the unconfined aquifer will be reduced. Any radionuclide inventory remaining in the tanks will slowly discharge into the vadose zone when natural recharge eventually contacts and leaches the residual waste. Conditions for migration to the unconfined aquifer would be comparable to those for dry waste disposal (essentially dry waste and low infiltration rates controlled by an engineered cover).

5.0 DATA AND ANALYSIS GAPS

5.1 INTRODUCTION

Data and analysis needs have been organized into a few categories. For each category, a description of the data or analysis need, the impact of the data or analysis on radionuclide migration, the current level of knowledge, the importance ranking, the feasibility of collecting more information (data needs only), the path forward, and the limitations of the derived information are discussed. For each category, impact levels are assigned using the expert judgment of the authors (see Appendix D for resumes). Significant components of expert judgment are as follows:

- Educational background
- Past observations of field and laboratory data relevant to radionuclide behavior in the soil-water environment at the Hanford Site
- Experience with transport modeling analyses designed to explain the conditions and processes that most affect radionuclide migration in the Hanford Site vadose zone and unconfined aquifer.

A data or analysis need is direct if the data or analytical result quantifies a condition or process that strongly influences eventual radionuclide contamination levels in the unconfined aquifer. A data or analysis need is intermediate if the data or analytical result quantifies a condition or process that moderately influences eventual radionuclide contamination levels in the unconfined aquifer. A data or analysis need is low if the data or analytical result quantifies a condition or process with minimal effect on eventual radionuclide contamination levels in the unconfined aquifer. These parameters, conditions, or processes are discussed for completeness. Finally, a data or analysis need is unclear if the effect of the process, condition, or analytical result on radionuclide migration is not known, but may be significant or provide a means to better understand the current and future distribution of radionuclides.

Current levels of knowledge are ranked as known, medium, low, and variable. The knowledge level is known if site-specific, quantifiable data are available to provide input into a radionuclide migration model and additional data will only marginally improve understanding. The knowledge level is medium if some site-specific, quantifiable data or relevant literature values are available. A medium database is considered sufficient to provide estimated values that can be put into radionuclide migration models and represent reasonably conservative assumptions. Using these estimates leads to conservatively high estimates of groundwater contamination. Additional data are expected to clearly improve both quantification of the condition or process and confidence in the values used in a radionuclide migration model. The knowledge level is low if no site-specific information is available and no general literature values can be used with confidence to represent the process or parameter in a radionuclide migration model. If the parameter or process is considered vital to the evaluation of radionuclide migration, additional data must be collected to develop usable values.

Considering both the determination of impact and knowledge level, the data or analysis needs are ranked for allocation of future resources.

- If the impact is direct and the knowledge level is low, a ranking of 1A is given and near-term resources should be devoted to implementing the path forward.
- If the impact is unclear and the knowledge level is low, a ranking of 1B is given and near-term resources should be devoted to implementing the path forward.
- If the impact is intermediate and the knowledge level is low, a ranking of 2 is given. If additional funding is available after resources are allocated to number 1 items, number 2 items should be addressed.
- If the impact is intermediate and the knowledge level is medium, a ranking of 3 is given. Resources can be spent on these needs to improve confidence in waste management decisions as necessary.
- If the impact is low and the knowledge level is known, medium, or low, a ranking of 4 is given. A ranking of 4 also is given if the impact is direct or intermediate and the knowledge level is known. In any of these cases, additional resources should not be spent because no real benefit can be derived.

The data and analysis needs are tabulated in Table 5-1.

5.2 RADIONUCLIDE DISTRIBUTION IN THE VADOSE ZONE ESTIMATES

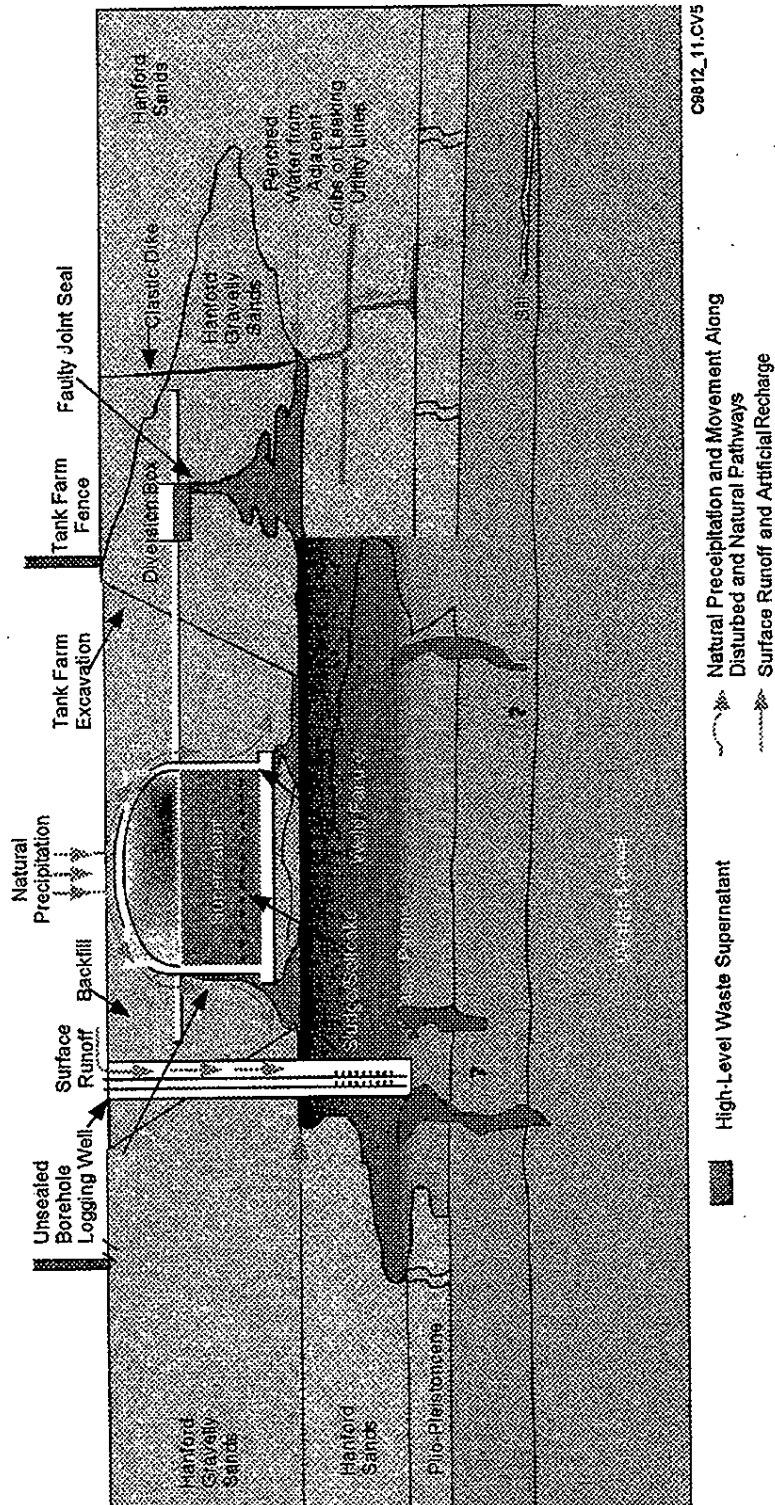
Figure 5-1 is a generalized schematic of the vadose zone contaminated by tank leaks. Note that the schematic includes leaks from other parts of the tank farm system involved in liquid waste transfers. The schematic only reflects single events and does not portray the potential for sequential leaks adding contamination or remobilizing previously discharged waste.

Radionuclide inventories in the vadose zone resulting from tank leaks can be estimated on the following basis: estimates of tank leak volumes and radionuclide concentrations in the leaked fluids at the time of the leak or characterization of the contaminated portions of the vadose zone. The necessary information is based primarily on indirect sources and only slightly on direct sources.

Table 5-1. Data and Analysis Needs Priorities.

Title	Information Type	Impact	Knowledge Level	Data Collection Feasible?	Ranking	Path Forward	Limitations
Radionuclide concentration in vadose zone	Data	Direct	Low	High	1A	Collect contaminated soils. Analyze for mobile and major radionuclides.	Small fraction can be sampled. Radioactive samples must be handled.
Spectral gamma logging data (SGL)	Data	Intermediate	Medium	High	3	Continue logging/maybe drill new boreholes.	Does not monitor LLMR. Data are from vertical point source.
Convert gamma logging data to inventory distribution	Analysis	Intermediate/low	Low	Use available data	2 or 3	Evaluate data on site-specific basis.	Extrapolating local measurements to total soil column introduces uncertainty.
Leak volumes	Analysis	Direct	Medium/low	Use available data	1A	Continue evaluating old data.	Old data ambiguous.
Composition of leaked tank waste	Analysis	Direct	Medium/low	Use available data	1A	Use Hanford (Site) defense waste model and review old data.	Old data ambiguous.
Correlation of estimated versus measured inventory	Analysis	Direct	Medium/low	Use available data	1A	Compare estimated versus measured data.	Limited availability and uncertain quality of data.
Geohydrology of vadose zone formations	Data	Direct/intermediate	Known/medium	High	3 or 4	Measure properties of site-specific soils.	Must extrapolate small sample value to large scale.
Geohydrologic properties of elastic dikes	Data	Intermediate/low	Low	Low	3 or 4	Difficult, perhaps impossible.	Probably no chance for success.
Geohydrologic properties of poorly cased boreholes	Data	Low	Known/medium	Low	4	Seal if necessary.	Not applicable.
Change in hydraulic properties in contaminated soils	Data	Unclear, but may be high	Low	High	1B	Collect contaminated soils. Measure properties and compare with properties of clean soil.	Must extrapolate data to large areas.
Waste chemistry effects on radionuclide mobility	Data	Low for mobile radionuclides, medium or low for sorbed radionuclides	Known/medium	Variable	Mobile radionuclides -4; sorbed radionuclides -2 or 3	Variable. None for mobile radionuclides, sorption/desorption tests on contaminated soils for sorbing radionuclides.	Empirical data must be assumed as representative.
Recharge effects of processing operations	Data	Direct to low	Low	Variable	2 to 4	Review data, perform lysimeter test, if necessary.	Data are derived from other sources and not a site-specific measurement.
Initial distribution of tank waste to soil	Analysis	Direct/intermediate	Medium/low	Use available data	1A or 2	Model each large waste discharge to soil.	Lack of data on leak volumes, leak rates, waste chemistry, and number of leaks for specific tanks.
Projection of contaminant migration	Analysis	Direct	Medium/low	Use available data	1A	Complete flow and transport models for site-specific contaminated zones.	Natural system heterogeneity and database uncertainty.
Temperature distribution in contaminated soils	Data	Low	Low	High	1B	Collect data	Historical temperature data lost. Heat transfer model needed.
Thermal effects on radionuclide-soil reactions	Data	Unclear	Low	Variable	2 to 4	Sample and analyze mineralogy of soils in hot zone.	Correlation of mineralogical changes with changes in radionuclide behavior uncertain
Thermal effects on physical transport rates	Data and analysis	Unclear	Low	Unclear	2 to 4	Complete literature search and sensitivity model with thermally adjusted hydrologic properties.	Hanford Site-specific data generally not available

Figure 5-1. Conceptual Model of Vadose Zone Contaminated by Tank Leaks.



The tank waste and leakage shown are from early operations in the 1960s. Subsequent hypothetical movement of contaminants through the vadose zone covers a period from early operations to the present. As a result of volume reduction measures, a much smaller volume of free liquid remains in the tank today. Depth to groundwater is 64 m (201 ft). The tank base elevation is about 15 m (50 ft) below ground surface. The geologic strata shown are simplified for illustration purposes.

5.2.1 Radionuclide Distribution in the Vadose Zone (Contaminated Soil Characterization Approach)

Estimates of radionuclide inventories in the vadose zone contaminated by tank leaks have not been thoroughly evaluated. Agnew (1997) provided some tank leak estimates as part of an overall tank inventory mass balance calculation. A few direct soil samples have been taken from one borehole beneath tank T-106 and analyzed for high-inventory radioactive constituents. Similar analyses are being completed for soil samples from beneath tanks SX-108 and SX-109. Otherwise, the most extensive characterization effort has been gamma logging in many drywells surrounding the tank farms and between the tanks. The gamma logging data provide three-dimensional qualitative indications of the location of gamma-emitting radioisotopes. Some evolution of the contaminated volumes also can be inferred from the database because logging measurements have been taken over time in some locations. Finally, because measured gamma intensities from logging data differ, an idea of relative concentrations in three dimensions is available. This information does not measure the location of non-gamma-emitting radionuclides, particularly the environmentally mobile radionuclides that apparently have contaminated and will continue to contaminate the unconfined aquifer.

Primary data and analyses to estimate radionuclide distribution in the leak-contaminated vadose zone are presented in Sections 5.2.2 through 5.2.6.

5.2.1.1 Quantifiable Radionuclide-Specific Concentrations in the Contaminated Vadose Zone (Particularly ^{99}Tc , Mobile Radionuclides, and Gamma Emitters) in Three Dimensions.

Type of Information. *Data.*

Impact. *Direct.* A primary goal of vadose zone characterization is to predict the level of groundwater contamination that will result from discharge of current vadose zone contamination into the unconfined aquifer. The predicted contamination level (radionuclide concentration) in the unconfined aquifer is almost proportional to the vadose zone inventory. These data allow the total radionuclide inventory in a specific location to be calculated.

Knowledge Level. *Low.* Sampling of soils contaminated by tank leaks accompanied by an analysis of most of the radionuclides of interest is limited to one borehole underlying tank T-106. Samples taken at depths just beneath the tank bottom level to the upper Ringold Formation were analyzed. Analyses of samples in the extension of one borehole underlying the SX tank farms are under way.

Feasibility of Collecting Additional Data. *High.* The technology for collecting and analyzing soil samples is well developed (borehole drilling and laboratory analysis).

Importance Ranking. *1A.*

Path Forward. Most zones contaminated by tank leaks have not been directly sampled. Given the limited resources, sampling and analyzing all suspected soil contamination sites is impossible.

Therefore, we must develop criteria to rank the sites by importance to decide the sampling order. Three important criteria for ranking contamination zones are the largest inventory of mobile radionuclides (e.g., ^{99}Tc), the largest total inventory, and the largest leak volume. These sites are most likely to provide the greatest contamination of the unconfined aquifer and are the most amenable to characterization.

Having determined the appropriate order of site characterization, the next step is to select the number and placement of additional boreholes to obtain optimum usable information as a function of available resources and tank farm-specific conditions. The obvious strategy is to sample the soil zones as close as possible to the leak location and sample as a function of depth.

Finally, determine the appropriate radionuclides to analyze for. The tank T-106 data support the hypothesis that ^{99}Tc is the most significant of the known environmentally mobile radionuclides and should be analyzed for routinely. Another mobile radionuclide, ^{129}I , has not been analyzed for, but should be. Cesium-137 is a large constituent of the contaminants and should be analyzed for to calibrate the gamma logging data, which then can be used to define the plume shape, at least near the leak source.

Limitations. Only a small fraction of the contaminated zone can be sampled, requiring extensive extrapolation of collected data. This may not be a severe limitation for mobile radionuclides, which tend to be distributed with leak fluid and are less likely to concentrate because of chemical reactions occurring in a localized region. Sample collection is made more difficult because radioactive samples must be handled.

5.2.1.2 Gamma Logging Data.

Type of Information. *Data.*

Impact. *Intermediate.* Spectral gamma logging provides a qualitative determination of the distribution of gamma-emitting radionuclides in the contaminated vadose zone. By taking measurements from many drywells as a function of depth and time, the general shape of the contamination zone and its evolution can be estimated. Generally, these data do not indicate mobile radionuclide distribution because the contaminants are not gamma emitters. One exception is the ^{106}Ru plume identified under tank T-106 soon after the leak event occurred. Laboratory and field data suggest that ^{106}Ru is highly mobile and may approximate the extent of leak fluid movement during the initial release phase. If mobile radionuclides such as ^{99}Tc migrate with the leak fluid, the ^{106}Ru distribution is an approximate marker for ^{99}Tc release. Unfortunately, ^{106}Ru is short-lived and no longer is present in sufficient quantity to be trackable. The other exception is ^{234}U , which can be identified by spectral gamma logging. These data are useful to estimate uranium migration if the leaked fluid contains a measurable amount of uranium.

Knowledge Level. *Medium.*

Feasibility of Collecting Additional Data. *High.* Many drywells are available for inserting gamma logging equipment and an active logging program is in place. The instrumentation has

been calibrated for the spectral gamma technique and allows specific radionuclide concentrations to be estimated based on the measured intensity of gamma radiation.

Importance Ranking. 3.

Path Forward. Additional logging is being completed and data will continue to be collected from existing drywells. If measurements from different locations are determined to be needed, drill new drywells and take measurements. Take this action only if the measurements will substantially enhance the understanding of contaminant distribution in the soil column of interest.

Limitations. Interpretation of gamma logging data is limited by several conditions. First, gamma logging can interrogate only out to about 30 cm (1 ft) from the borehole. The gamma rays can penetrate only about 30 cm (1 ft) of soil. If a hot spot develops outside this range, it can be discovered only by installing additional drywells and taking more measurements. Historically, gross gamma measurements that have been taken do not distinguish between specific isotopes and could not be calibrated to specific isotopic concentrations. Gamma logging data are further limited by the well drilling techniques used to construct the wells from which the logs are obtained. Numerous instances are recorded where the drilling activity resulted in cross-contamination of zones in wells. While being advanced, casing is in contact with the formation and often carries materials downward. Drilling tools often carry contaminated material upward as the tools are operated or retracted from the bore. Dragdown of contamination was apparent in boreholes 41-09-39 (during construction and extension) and in 41-12-01, even though considerable effort was made in all instances to minimize its occurrence.

5.2.1.3 Extrapolating Gamma Logging Intensities to Gamma-Emitting Radionuclide Distributions.

Type of Information. *Analysis.*

Impact. *Intermediate.* Same as Section 5.1.2.

Knowledge Level. *Low.* To correlate gamma intensities with actual radionuclide concentrations, measurements from soil volumes containing known quantities of the radionuclides of interest are needed to convert gamma intensities measured in soils of unknown contamination levels. This calibration process has been completed for recent measurements using spectral gamma intensity measurements. Concentration estimates for individual drywells are available for ^{137}Cs and ^{60}Co . Simple extrapolations of gamma data between drywells have been done, but their validity has not been demonstrated. Given the tendency of the primary gamma emitter (^{137}Cs) to concentrate in specific soil zones, such extrapolations probably are speculative.

Importance Ranking. 2.

Path Forward. Evaluate available data on a site-specific basis and estimate total inventories for specific gamma-emitting radionuclides. These estimates can be compared to estimates of total inventory released in the leaked fluids (see Section 1.3). If the estimates are reasonably close

(e.g., within a factor of 5), some confidence can be gained in the current inventory estimate and gamma-emitting radionuclide distribution in the vadose zone.

Limitations. As explained in Section 2.1.2, the data truly apply only within a small distance from the measuring apparatus. Extrapolating concentrations from point to point gives uncertain results, particularly for chemically reactive radionuclides. Most gamma emitters found in contaminated soil are chemically reactive and will provide little insight into mobile radionuclide behavior.

5.2.2 Radionuclide Distribution in the Vadose Zone (Source Term Estimate Approach)

Where leak volume and radionuclide concentrations are used, process knowledge is the primary source for radionuclides (most recently, Agnew [1997]). For a few tanks, samples of actual liquors have been collected and analyzed, although infrequently for the radionuclides of greatest concern (those that are environmentally mobile). Leak volumes are estimated by measuring changes in the liquid level inside tanks. In many cases, leaks are suspected, but evidence of leakage is not clear. For these tanks, a minimum leakage value has been assumed. Data needed to estimate radionuclide distribution in the leak-contaminated vadose zone are addressed in Sections 5.2.2.1 and 5.2.2.2.

5.2.2.1 Leak Volumes.

Type of Information. *Analysis.*

Impact. *Direct.* The predicted contamination level (radionuclide concentration) in the unconfined aquifer varies almost proportionally with the vadose zone inventory. One method for estimating the radionuclide inventory leaked into the vadose zone is to take the product of the estimated leak volume and each radionuclide concentration in the leaked fluid. By doing this calculation for each tank or tank farm, one can calculate the total radionuclide inventory in a specific location.

Knowledge Level. *Medium/Low.* The most direct indication of leak volumes for a particular tank is measured changes in liquid level inside the tank and process records of liquid transfer from tank to tank. The usefulness of this information and confidence in the leak estimates vary from tank to tank. Large, short-duration leaks are the most easily estimated.

Feasibility of Collecting Additional Data. *Negligible.* The leak events are over and the opportunity to collect additional data has passed.

Importance Ranking. *1A.*

Path Forward. Most SSTs have been pumped to the extent that no free liquids are available to leak. Consequently, a new leak event is unlikely and undesirable. Continue evaluating old processing information and leak data to better estimate leak volumes.

Limitations. Additional information leading to estimates or measurements of leak volumes cannot be collected because the leaks already have occurred. Some leaks were small enough that even indirect measurements used to detect and measure the extent of the leak (e.g., liquid level changes) are ambiguous.

5.2.2.2 Radionuclide Concentrations in Leaked Fluid.

Type of Information. *Analysis.*

Impact. *Direct.* See impact discussion in Section 5.2.2.1.

Knowledge Level. *Medium/Low.* Radionuclide concentrations have been based on process knowledge (the type of process that generated the waste and the tank or tanks receiving the waste fluid) and, to a much lesser extent, sample analyses. In general, only a small subset of radionuclides was analyzed for and typically did not include ^{99}Tc or other mobile radionuclides.

Feasibility of Collecting Additional Data. *Low.* Tank fluids are no longer present in most SSTs and the opportunity to sample the tank liquid has passed. Further, any remaining liquid in SSTs that have previously leaked is unlikely to accurately represent the leaked fluid.

Importance Ranking. *1A.*

Path Forward. Continue reviewing available data to increase confidence in radionuclide concentrations in leaked fluids. Using Agnew's model to predict fluid compositions when the leak occurred also could be useful.

Limitations. Additional information leading to estimates or measurements of radionuclide concentrations in leak volumes cannot be collected because the leaks have occurred and leak fluids are not available for analysis.

5.2.3 Correlation of Radionuclide Estimates with Source and Vadose Characterization Information

Type of Information. *Analysis.*

Impact. *Direct.* If estimates of the radionuclide inventory currently in the vadose zone can be reasonably correlated with initial leak conditions and the vadose characterization data, confidence in our estimates of current contamination conditions will increase substantially. This is particularly important for known mobile radionuclides expected to ultimately contaminate the underlying aquifer. Similarly, if radionuclides normally considered to be nonmobile are shown to be permanently mobilized because of tank leak effects on the local soil column, a correlation analysis should be completed.

Knowledge Level. *Medium/Low.* Radionuclide inventories based on leaked tank fluid characterization cannot be compared with radionuclide inventories estimated from vadose zone characterization data for all radionuclides for any soil zones contaminated by tank leaks. The necessary information is not available. Currently, the most complete data set available is for the tank T-106 leak. However, any attempts to complete a correlation analysis have not been published.

Importance Ranking. *1A.*

Path Forward. Complete a correlation analysis for each primary soil contamination zone. Consider inventories from all tanks contributing inventory to the contaminated zone. Analyses will be considered successful when a reasonably close (e.g., within a factor of 2) correlation in inventory estimates is demonstrated for the set of radionuclides of greatest concern (typically, mobile radionuclides, primarily ^{99}Tc , and major constituents, such as ^{137}Cs). When this analysis and adequate hydrogeologic characterization are successfully completed, sufficient information should be available to project future groundwater contamination and make waste remediation decisions. The success of a correlation analysis can be used to determine the adequacy of a characterization effort.

Limitations. The success of the correlation analysis depends on the existence and accuracy of the pertinent information. In some cases, the necessary information probably will not be available.

5.3 GEOHYDROLOGIC PROPERTIES

The current knowledge of the three-dimensional arrangement of tank-leak-contaminated vadose zone soils indicates that specific local geohydrologic features have significantly influenced the distribution of tank leak fluids during the leak event and will continue to influence further contaminant movement toward the unconfined aquifer. Other features exist that potentially could be significant. Geohydrologic features are ubiquitous or sporadic. Ubiquitous features are present across most, if not all, of the contaminated zone. These can be distinct and continuous formations or large lenses of homogeneous materials (e.g., clay-rich sediments imbedded in sand-rich sediments). Sporadic features are linear features that could provide preferential pathways for contaminant transport to the unconfined aquifer. These are primarily clastic dikes. Inadequately sealed boreholes are included because their potential effect on contaminant transport is similar.

5.3.1 Geohydrologic Properties of Vadose Zone Formations

Type of Information. *Data.*

Impact. *Direct/Intermediate.* One geologic unit underlying the 200 West Area tank farms that appears to have greatly influenced tank fluid distribution in the vadose zone is the Plio-Pleistocene unit because of its relatively low permeability and high calcite content. The tank T-106 database suggests that, at least temporarily, the Plio-Pleistocene acted as a barrier to downward movement of the leaking fluid. If true, this effect has delayed the discharge of most of the leaked

contaminants into the unconfined aquifer and dispersed the contaminants laterally. Further, the delay has reduced future release rates into the unconfined aquifer because the downward hydraulic driving force from the leak, which has dissipated, was greater than the driving force of recharge currently coming from precipitation. All geologic units and subunits have characteristic hydraulic properties and unit thicknesses that have influenced and continue to influence leak fluid distribution, but their properties do not have the same impact on contaminant transport as the Plio-Pleistocene unit. Lenses of clay-rich sediments that might trap moisture and sorb radionuclides more highly are difficult to find from a few borehole samples, and contaminant concentrations associated with clay-rich sediments generally are not measured directly.

Knowledge Level. *Known/Medium.* As a result of numerous site characterization efforts, for each major formation in the vadose zone, average soil mineralogy characteristics have been determined, and average physical and hydraulic property values have been measured. Some idea of variability in these properties also is known. Variability in formation thickness also is reasonably well known throughout the Hanford Site. On the other hand, site-specific properties have not been measured for most of the leak-contaminated soils in the vadose zone. Naturally, uncertainty associated with hydraulic property measurements determined in the laboratory is greater than the uncertainty associated with field measurements because samples taken from boreholes are very small relative to the natural soil volume and they must be reconstituted to perform the test.

Importance Ranking. 3/4.

Feasibility of Collecting Additional Data. *High.* Additional physical and hydraulic property data can be determined by taking soil samples from the contaminated zone of interest and completing the appropriate characterization analysis or hydraulic property test in the laboratory. Significant hydraulic properties are the relationships between moisture content and matric potential and between unsaturated hydraulic conductivity and moisture content.

Path Forward. Given the state of knowledge about formation properties, collecting additional soil samples in the contaminated zone specifically to collect this kind of information is not warranted. However, if soil samples are collected for other reasons (e.g., measurement of contaminants), measuring soil properties to improve confidence in modeling exercises designed to project future migration of contaminants is recommended.

Limitations. As with all soil samples, some uncertainty is generated by extrapolating property data from a small sample to a much larger soil volume. Extrapolating data taken from a formation at one location to the same formation at another location also generates uncertainty. However, this extrapolation process is fairly reasonable because soil properties within any given formation do not vary excessively.

5.3.2 Geohydrologic Properties of Clastic Dikes

Type of Information. *Data.*

Impact. *Intermediate/Low.* Clastic dikes are linear cracks that may provide preferential pathways for contaminants because they are filled with sediments that are distinguishable from the surrounding sediments. Commonly, distinguishing attributes are different mineralogical make up and/or different particle size distributions. If the clastic dike materials are more permeable than the surrounding soils, a preferential pathway is plausible. These features are unlikely to be significant pathways on the scale of the contaminated soil volumes because they are small and discontinuous, and their three-dimensional orientations frequently have a strong horizontal component.

Knowledge Level. *Low.* Clastic dikes have been observed in numerous places, usually where large excavations were made. Hydraulic properties of clastic dike materials have never been measured, probably because representative samples generally are difficult to procure.

Importance Ranking. *3/4.*

Feasibility of Collecting Additional Data. *Low.* Identifying clastic dikes in an area where few boreholes are drilled cannot be guaranteed because of their random nature and small cross section. Attempts to measure relevant properties are likely to be unsuccessful.

Path Forward. Mapping and characterizing clastic dike properties is difficult, perhaps impossible. If appropriate, complete sensitivity modeling to determine the potential impact of these features.

Limitations. Identifying clastic dikes in an area where few boreholes are drilled cannot be guaranteed and measuring relevant properties is likely to be unsuccessful.

5.3.3 Geohydrologic Properties of Poorly Cased Boreholes

Type of Information. *Data.*

Impact. *Low.* High-permeability zones next to boreholes are significant only if they exist in or near enough to the contaminated zone to provide a preferential path. Further, the borehole would have to be permanently left open to continue facilitating contaminant migration.

Knowledge Level. *Known/Medium.* Borehole locations near or in tank-leak-contaminated zones are well known. Few extend to the water table.

Importance Ranking. *4.*

Feasibility of Collecting Additional Data. *Low.* Cavities left around borehole casings are difficult to detect unless tracers or contaminants that can be traced to the borehole show up in the groundwater.

Path Forward. Identify the existence of boreholes near contaminated zones that might be potential preferential pathways. Plug boreholes immediately if groundwater contamination is clearly a result of the borehole opening. Otherwise, fill in boreholes as part of the closure process.

Limitations. *Not Applicable.*

5.4 TEMPORARY AND PERMANENT GEOCHEMICAL CHANGES INDUCED BY LEAKING FLUID CHEMISTRY

The chemical properties of leaked tank fluids are substantially different from those of natural water. Interaction with soils probably introduced temporary geochemical changes in the soil column near the tank bottom and may have created permanent changes in the soil-water environment that change radionuclide migration characteristics. The following primary types of potential changes have been identified:

- Changes in the hydraulic properties of the soil matrix
- Changes in the chemical reactivity of some radionuclides
- Changes in the mineralogy of the soil matrix.

These changes are discussed in Sections 5.4.1 through 5.4.3 as a function of known environmentally mobile radionuclides versus normally reactive (sorbing) radionuclides whose mobility might be increased because of geochemical changes in the contaminated soil zone.

5.4.1 Changes in Hydraulic Properties

Type of Information. *Data.*

Impact. *Unclear.* Because most tank liquids were high-pH and, frequently, high-temperature fluids, they could dissolve existing minerals and reprecipitate other solids. If the net effect is to increase the solids volume and decrease porosity, reduced permeability could result. Conversely, preferential flow channels could be formed to enhance fluid contaminant migration. Despite the lack of real evidence, this effect should be limited to an area near the leak source and should not be particularly significant to the total contaminated vadose zone-unconfined aquifer system. Evidence of enhanced migration of radionuclides could result from increased soil column permeability, but other conditions are more likely the cause. For example, ^{106}Ru dispersed down to the Plio-Pleistocene formation shortly after the tank T-106 leak event. The influence of the large hydraulic driving force created by rapid discharge of a large volume of water from the tank is more likely than increased soil column permeability to be the significant factor.

Knowledge Level. *Low.* Indirect evidence in the form of distributed contaminants in the soil column indicates that substantial permeability changes are unrealistic. No direct evidence in the form of actual soil characterization is available.

Importance Ranking. *1B.*

Feasibility of Collecting Additional Data. *Medium/Low.* Collecting soil samples from borehole emplacement is straightforward, although radioactive contamination makes the process cumbersome and expensive. Therefore, the number of samples that can be collected will be small. Mineralogic examination also is routine. Hydraulic properties can be measured. However, in situ physical changes are difficult to preserve when sampling, and reconstituting soils for hydraulic testing always adds uncertainty to the measured properties.

Path Forward. Analyze future soil samples taken from the contaminated vadose zone for solid-phase mineralogy, particularly from the areas nearest the leak source, and compare the samples with uncontaminated soils. If significant dissolution and reprecipitation phase changes are evident, consider performing hydraulic property tests on these samples. Decide on the appropriate fluid composition to use and whether to collect data on saturated and/or partially saturated materials.

Limitations. As with all soil samples, extrapolating the characterization to larger soil volumes around the soil sample location creates uncertainty.

5.4.2 Tank Liquid Chemistry Effects on Radionuclide Mobility

Type of Information. Data.

Impact. *Mobile Radionuclides, Low.* Known mobile radionuclides are those present in the unconfined aquifer. These include ^{99}Tc , tritium, ^{129}I , and uranium. Of these, the present database suggests that ^{99}Tc is the most abundant mobile radionuclide in tank leak fluids. The chemical characteristics of tank fluid (primarily highly caustic and high-salt concentrations) do not chemically influence ^{99}Tc mobility.

Sorbing Radionuclides, Medium/Low. Increase in the pH and salt content in fluid will influence only some sorbing radionuclides. If a particular radionuclide's mobility is enhanced, a long-term detrimental impact on groundwater must be evaluated. A significant increase in groundwater contamination is not necessarily an outcome. Four scenarios are plausible, depending on the radionuclide properties. First, the mobility of a particular radionuclide may be sufficiently enhanced to result in groundwater contamination in the foreseeable future (e.g., within 100 years). Second, the enhanced mobility may be only temporary and the radionuclide, while penetrating the vadose zone to greater depths during enhanced mobility, will not reach the unconfined aquifer within the appropriate time frame. Third, an increased rate of migration may be permanent because of reduced sorption, but the rate might not be increased sufficiently to permit transport to the water table within an appropriate time frame (e.g., 1,000 years or more).

Fourth, radionuclide decay may reduce the radionuclide inventory to negligible levels before discharge into the unconfined aquifer, making any mobility changes irrelevant.

Knowledge Level. *Mobile Radionuclides, Known/Medium.* The behavior of mobile radionuclides over the range of existing conditions in Hanford Site soils has been evaluated to varying degrees, both in laboratory experiments and using field-scale measurements and observations. The available data suggest that mobile radionuclides maintain their mobility in soils contaminated by leaks.

Sorbing Radionuclides, Medium/Low. Some laboratory studies have been completed that evaluate mobility of selected radionuclides under chemical conditions that simulate tank fluid chemistry-soil interactions (Ames and Rai 1978). Several of the primary radionuclides have been evaluated. Presently, both the laboratory data and field data suggest that the mobility of ^{137}Cs has been enhanced, at least temporarily, probably because high sodium content in the liquid competing successfully for sorption sites with ^{137}Cs . The tank T-106 data indicate that plutonium's mobility also may be enhanced, perhaps as a result of complexing with chelating agents. However, the cause of enhanced mobility is not obvious.

Importance Ranking. *Mobile Radionuclides-4.*
Sorbing Radionuclides-2/3.

Feasibility of Collecting Additional Data. *Variable.* Empirical evidence of radionuclide behavior can be collected with standard soil characterization tests and batch or flow-through sorption tests in the laboratory. Isolating and identifying specific mechanistic processes and system variables controlling these processes can be investigated, but the processes and variables are unlikely to be clearly understood or quantifiable. The following examples show potentially useful mechanistic information that is difficult to determine experimentally.

- Measuring sorptive capacity of different mineral phases for a particular radionuclide
- Identifying specific mineral phases controlling sorption
- Determining the reversibility of sorption reactions with particular pairs of radionuclides and mineral phases
- Documenting the effects of specific organic and inorganic species precipitated or sorbed from the tank liquid on sorption reactions
- Measuring changes in water chemistry in the vadose zone caused by reduced moisture content or changes in moisture content at the interface between different hydrologic units.

Path Forward. *Mobile Radionuclides, None.* Unless some observation indicates that mobility is reduced for mobile radionuclides, no additional work is needed.

Sorbing Radionuclides. To properly evaluate potentially enhanced mobility of sorbing radionuclides, identify radionuclides presently entrained in the contaminated soil. Collect soil samples and analyze for radionuclides already identified from analyzing tank supernatant liquids and gamma logging. Analyze soil samples from boreholes for mineralogy and the presence of chemical species precipitated or sorbed from the tank liquid. If possible, extract moisture from soil samples and determine the chemical composition. Complete desorption and sorption tests with soil samples to evaluate the mobility of identified sorbing radionuclides. Typically, an empirical sorption coefficient can be quantified. Compare empirical sorption and desorption coefficients with those found for natural soil-water environments.

Experiments constructed to evaluate specific mechanistic processes controlling radionuclide mobility are not recommended. The basic approach is to break the complex environmental system into small subsystems (e.g., sorption of one radionuclide on one mineral phase), measure radionuclide behavior, and, from the collected results, identify the dominant processes. This approach is time consuming and can generate misleading results if important synergistic reactions occurring in the natural system are eliminated when the subsystem is selected.

Limitations. Empirically designed experiments to quantify radionuclide behavior and field observations of radionuclide behavior are generally unsuccessful at quantifying the specific processes that control mobility in a complex soil environment. However, if a fair comparison between laboratory and field empirical data that quantifies environmental mobility can be established, and modeling analyses using these inputs show reasonable correlation with field observations, the level of confidence in predicting future radionuclide behavior is reasonable and waste management decisions can be made.

5.5 TEMPORARY AND PERMANENT RECHARGE CONDITIONS INDUCED BY TANK OPERATIONS, LEAKS, AND STRUCTURES

Depending on the contaminated vadose zone site, three types of hydraulic drivers other than tank leaks may have acted or continue to act to distribute contaminants in the vadose zone. The first consists of leaks from tank bottoms and overflows from tanks or transfer lines as liquid was shifted between tanks. These are sporadic events that discharge large volumes of liquid into the soil column over a short term, creating plug flow through a localized soil volume. The plug flow events create temporary saturated flow in a limited portion of the soil column. The second is chronic discharge from underground pipes, valve boxes, or diversion boxes. These discharges may be ongoing currently, but are difficult to detect. The third is chronic concentrated recharge (relative to normal recharge through undisturbed soil) of precipitate through the soil columns around the perimeters of the tanks. This enhanced recharge is still unsaturated flow. This type of concentrated recharge occurs because of the high-permeability covers over tank farms (unvegetated gravel) and impermeable tank covers that divert infiltrating water to the outside of the tank walls.

5.5.1 Recharge Conditions and Rates Created by Hanford Site Processing Operations Other than Leaks from Tank Bottoms

Type of Information. *Data.*

Impact. *Variable* The tank structure creates an impermeable shield over the underlying soil column that precludes recharge and creates a concentrated recharge zone around its perimeter because of runoff from the tank roof. Recharge outside the tank umbrella is further enhanced relative to natural conditions because the surface cover is gravel kept free of vegetation. This surface minimizes water storage and evapotranspiration processes.

Tank overfills and leaks from other sources within the tank farm system (e.g., transfer lines) also may have provided and may continue to provide additional contaminants and a hydraulic driving force in the vicinity of tank leaks. The significance of these events depends on the location of the leak, the size of the leak, and the degree of contamination in the leaked fluids.

Additional water also may be introduced into the contaminated soil zone from nearby cribs and trenches that have received large volumes of water. Some of that water may have moved laterally, depending on the soil characteristics and discharge rate of waste water through the crib or trench, and intruded into the contaminated soil zone. If so, an additional driving force for moving contaminants downward exists. Other water may have been added to the soil column from septic fields around tank farms.

Knowledge Level. *Low.* None of the processes or hydrologic effects of processes associated with Hanford Site operations are completely identified or quantified. Estimates of recharge at the tank perimeters have been estimated based on lysimeter tests with gravel, but they have not been verified. The runoff component has been estimated but not tested. Some leaks from transfer lines can be inferred from fluid losses observed and noted in processing records or may be inferred from gamma logging. Some deliberate tank overfill events were recorded. Other potential sources of fluid (septic fields, cribs, and trenches) have not been evaluated as potential contributors to migration of tank leak contaminants.

Importance Ranking. *1B*

Feasibility of Collecting Additional Data. *Variable.* Moisture movement at the edges the tank where runoff collects and enhanced recharge are expected and can be measured directly. The feasibility of determining whether fluids and contaminants from other sources were added to the tank-leak-contaminated soil zones is low. Evidence of these contributions generally is known from records, and details of volume and radionuclide content are sketchy.

Path Forward. For each soil contamination zone of concern, the path forward is to identify events or processes that may have affected or continue to affect that soil volume and estimate the volumes of liquid discharged, the duration of the event, and the contamination associated with additional fluids. Determine which sources should be considered for input into the modeling exercise. For recharge around the tanks, measure moisture movement with lysimeters or estimate

recharge from other lysimeter studies and modeling analyses that have attempted to estimate the runoff contribution.

5.5.2 Initial Distribution of Tank Leak and Other Large-Volume Leaks (Tank Spills, Transfer Line Leaks, Large Surface Spills)

Type of Information. *Analysis.*

Impact. *Direct/Intermediate.* Future migration of radionuclides currently distributed in the vadose zone depends to a large extent on the present configuration. This is particularly important for mobile radionuclides that theoretically will travel with the leaking fluid and are likely to contaminate the unconfined aquifer in the foreseeable future. Evaluating how well the current condition can be simulated from the initial event, then projecting the future migration into the unconfined aquifer is useful for developing confidence in future projections. Also, when considering future sluicing operations in which similar tank leaks might be reactivated, these analytical results will be helpful in determining the relative risks of various waste removal options.

Knowledge Level. *Medium/Low.* Field evidence to date suggests that the most extensive distribution of contaminants resulting from the large leaks resulted primarily from the initial event and the hydraulic forces associated with the leaks. The hydraulic forces that have acted on the leaked fluids remaining in the vadose zone have not been analyzed.

Importance Ranking. *1A/2.*

Path Forward. To analyze the migration of the tank leak volume or other large-volume leaks, a hydrologic model must be exercised for each contaminated soil volume. Either a two- or three-dimensional model can be used. Numerical two- and three-dimensional codes have been developed and used to predict contaminant transport from surface or near-surface Hanford Site waste through the vadose zone into the unconfined aquifer (e.g., Wood et al. 1995). The mathematical approach is robust and accepted in the technical community.

Key input data for estimating the initial distribution of the leak fluid include tank leak history and hydraulic properties of the soil column. Other large leaks resulting from tank overflows and transfer line leaks must be considered separately or with tank bottom leaks, depending on location, which determines the potential for commingling. The analyses should illuminate the environmental parameters to which contaminant distribution is most sensitive during the leak event.

Limitations. Numerous uncertainties are associated with this kind of analysis. The greatest uncertainties tend to be knowledge of the actual leak volume, rate of release, and the effects of heat on the rate of liquid movement and chemical reactions on the hydraulic properties of the soil column. For transfer line leaks and surface spills, the location and timing of the leak are not well known. If multiple events have occurred close enough together, the combined leak volume distribution will be difficult to estimate. Finally, heterogeneities in the soil column geology and

associated changes in hydrologic properties may be large enough to affect fluid distribution, but not large enough to be measured or detected.

5.5.3 Projected Migration of Tank Leaks and Other Large Volume Leaks (Tank Spills, Transfer Line Leaks, Large Surface Spills)

Type of Information. *Analysis.*

Impact. *Direct.* Future migration of radionuclides from their current distribution in the vadose zone depends greatly on the hydraulic forces controlling discharge of contaminated water into the unconfined aquifer. This is particularly important for mobile radionuclides that, theoretically, will travel with the leaked fluid and are likely to contaminate the unconfined aquifer in the foreseeable future. In addition to the present configuration of contaminated fluids, other leaks and ongoing recharge processes influence the ultimate discharge of contaminants into the unconfined aquifer to varying degrees.

Knowledge Level. *Low.* Limited field evidence from available vadose zone characterization and groundwater sampling near the tank farms indicates that the majority of radionuclide inventory leaked from tanks remains in the vadose zone. Therefore, future aquifer contamination from this source must be estimated. The primary environmental parameters affecting this stage of contaminant migration include hydrologic properties of the contaminated soils, sorption reactions of radionuclides, enhanced recharge between tanks, and decreased or nonexistent recharge directly under the tanks. Other factors of significance may be residual heat load in leaked fluids, migration of liquids from nearby crib and trench discharges, and additional tank leaks from future sluicing operations.

Although the mathematical approach to predicting contaminant transport (e.g., Wood et al. 1995) is robust and accepted in the technical community, the success of the modeling depends primarily on the availability and quality of the input data. Currently, no significant attempt to model radionuclide migration from soil zones contaminated by tank fluids has been completed.

Importance. *1A.*

Path Forward. Derive projections of future contaminant migration by continuing the hydrologic modeling approach described in Section 4.2. In this case, however, the relatively important parameters controlling contaminant migration should be chronic recharge processes rather than large leak events. Choose parameter values that are considered to provide reasonably conservative (high, but not worst case) estimates of groundwater contamination. Use these analytical results to provide insight into immediate issues (e.g., the potential consequence of in-tank waste retrieval options). Iterate the modeling analyses as additional data are developed.

Limitations. As with any modeling exercise, uncertainty in the validity of the results is generated from the starting inventory characteristics (total inventory, spatial concentrations, and distributions in the soil column) and heterogeneity in the hydrogeologic properties of the

contaminated soil site. This, coupled with the necessity of modeling the migration of contaminants in a general and therefore simplified and approximate fashion, requires that modeling results be considered tools for making waste remediation decisions rather than completely accurate predictions of future events.

5.6 THERMAL EFFECTS

5.6.1 Temperature Distribution in the Contaminated Soil Zone

Type of Information. *Data.*

Impact. *Low.* Depending on the radioactivity initially present in the leaking fluid and the leak volume, heat transferred to the soil column varied. Heat continues to be generated by radioactive decay of radionuclides remaining in the soil column. Above-normal temperatures have been recorded in boreholes underlying the SX tank farms, showing that thermal energy has not been entirely attenuated in the local environment. The observation of higher groundwater temperatures suggests that some of the leaked fluid has already reached the unconfined aquifer. This observation does not directly identify the influence of elevated temperature on contaminant migration. Rather, a thermal signature may best be considered a potentially valuable tracer defining contaminant and liquid migration.

Knowledge Level. *Low.* A spatial and temporal temperature database is not available.

Importance Ranking. *1B.* These data may be significant if they are determined to accurately indicate current leak fluid or contaminant distribution.

Feasibility of Collecting Additional Data. *High.* Temperature measurements can be taken from all available drywells and from groundwater samples.

Path Forward. Collect available temperature data from dry wells and determine completeness of data set. If sufficiently complete, extrapolate data to a three-dimensional configuration and compare them with gamma logging information. A one-to-one match would be unlikely, but trends should be similar. If appropriate, use thermal hot spots to guide sampling and analysis of the soil column.

Limitations. Data not collected at the time of the leak cannot be retrieved. Therefore, a chronological evolution of temperature profiles is limited by historical record. Attenuation of thermal energy is not expected to correspond one to one with liquid distribution. Extrapolation is always uncertain, but may be more reliable than gamma logging because thermal spreading is not influenced by chemical reactions in the same way as radionuclide movement. To aid in interpreting the data, additional analyses that project heat transfer in the contaminated soil column might be worthwhile.

5.6.2 Thermal Impacts on Radionuclide-Soil Chemical Reactions

Type of Information. *Data.*

Impact. *Unclear.* The general effects of increased temperature on chemical reactions is to increase the rate of reaction and, depending on the system constituents, change the type of reaction taking place. Thermal effects must be considered in conjunction with the anomalous chemical nature of the leaking fluids. The significance of this process depends on its effect on radionuclide mobility. If a radionuclide is normally moderately to strongly sorbing, it probably will not reach the unconfined aquifer in around 1,000 years or less. If the thermal effects coupled with fluid chemistry have the long-term effect of enhancing the radionuclide's mobility such that it can reach the unconfined aquifer in the short term, the impact is high.

Knowledge Level. *Low.* Neither laboratory nor field data are sufficient to quantify thermally induced changes in the mobility of normally sorptive radionuclides found in the contaminated soil column.

Importance Ranking. *2-4.*

Feasibility of Collecting Additional Data. *Variable.*

Path Forward. Define the temperature range likely to have occurred in the contaminated zone, either by direct measurement or by calculation. Conduct a literature search to determine the database for radionuclide behavior at elevated temperature. Sample soils in the thermally hot zones to determine any permanent change in soil mineralogy. Evaluate the likelihood that thermal effects could cause radionuclides present in the soil column to become sufficiently mobile to contaminate the aquifer. Perform sorption-desorption tests on altered soils at temperature or experimentally alter soils using leak fluid chemistry and temperature, then perform sorption-desorption tests.

Limitations. The primary limitation of this process is that empirical data are provided that do not necessarily illuminate the processes or significant environmental parameters that control radionuclide behavior. The usefulness of empirical data depends on the experimenter's ability to accurately recreate the environmental conditions under which radionuclide migration occurred. Because the environmental conditions have clearly changed between the initial event and the present, previous conditions must be estimated. For example, if soils must be altered experimentally to simulate real alterations, uncertainty is created about the representativeness of the altered material relative to actual radionuclide behavior.

5.6.3 Thermal Impacts on Rate of Physical Transport

Type of Information. *Data and Analysis.*

Impact. *Unclear.* Heated fluids naturally travel at an enhanced rate because of an overall increase in system energy. However, the relative change is not easily quantified. The thermal

effects decrease over time as a function of radioactive decay and attenuation in the soil column. Thermal effects may or may not significantly enhance contaminant transport. Given that thermal impacts have diminished and were not initially severe at some sites, long-term significant impact is not expected.

Knowledge Level. *Low.* Field or laboratory data do not exist to quantify the physical effects induced by heated fluid. Contaminant migration analyses that couple hydraulic and thermal driving forces have not been completed.

Importance Ranking. *2-4.*

Feasibility of Collecting Additional Data. *Unclear.* Site-specific data that document the effects of elevated temperatures on the hydraulic effects on leaking tank fluids or hydrologic properties are not available. Corollary information may be available in the literature.

Path Forward. To account for the influence of thermal driving forces in the tank leak event, derive hydraulic property data that reflect the influence of elevated temperature. Because Hanford Site-specific data are not available, complete a literature search to quantify these properties. Compare these properties with available properties for normal conditions and determine if a sensitivity analysis is worth developing.

Limitations. Data are not available that measure standard transport properties of tank fluids migrating through the Hanford Site vadose zone soil at elevated temperatures. Similarly, lateral migration tendencies in partially saturated soils for these kinds of fluids are not known.

6.0 PATH FORWARD

A number of critical data gaps have been identified in Chapter 5 from an assessment of the information presented in Chapters 2 through 4. The major areas of uncertainty are the following: site-specific contaminant distribution in the vadose zone and the identification of the site-specific events and processes dominating contaminant distribution. Until these uncertainties are reduced, an evaluation of the consequences of future leaks caused by waste retrieval operations will be correspondingly uncertain. Additional boreholes for sampling and analysis may be required to address the identified critical data gaps. The planning process for vadose zone characterization will address additional data needs to support TWRS decisions.

From discussion on the generalized conceptual model of tank leaks, clearly, infiltration (both natural from meteoric sources and artificial from operations-related sources), inventory, and contaminant mobility are important factors affecting the nature and extent of contaminant migration in tank farm vadose zones. Of these three factors, the most readily controlled is the contribution of infiltration to contaminant migration. For example, as an alternative to existing gravel covers in tank farms, interim covers would reduce infiltration and transport of mobile contaminants before the tank farms are closed and also lessen the impact of potential losses to the vadose zone during tank waste retrieval. However, gravel covers perform an important function in minimizing radiation exposure to tank farm workers. Therefore, decisions on controlling surface infiltration must consider tradeoffs between near-term worker health and safety issues and longer term impacts to groundwater. Natural recharge is enhanced by infiltration of water ponded over and around tanks from weather events, water line leaks, and ancillary tank farm-related equipment operations. Thus, minimizing water line leaks and water losses from ancillary equipment and channeling surface water flow away from tank farms are important and effective corrective measures for controlling vadose zone contamination migration in tank farms.

A number of factors, such as the leak characteristics, waste chemistry, geology, hydrology, weather events, and tank farm operational activities, may differentiate the consequences of a tank leak on the vadose zone. The objectives for characterizing vadose zone soils will be developed and included in site-specific work plans. Ultimately, cleanup decisions affecting all contaminated sites will be based on conclusions drawn from a relatively small number of samples. Care in selecting sample locations will allow broad application of results and conclusions.

The conceptual understanding of impacts of unplanned releases of tank wastes into the vadose zone, discussed in Chapter 4, is considered an initial model from which more detailed conceptual models would be developed during site-specific planning activities. Such site-specific conceptual models may supersede the conceptual model presented in Chapter 4 or simply refine it, depending on the detailed analysis of site-specific information.

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APPENDIX A
GEOLOGY AND STRATIGRAPHY OF THE TANK FARMS¹

¹From *Assessment of Geologic Data Relevant to Hanford Site Single-Shell Tank Farms and Generalized Geologic Models for the Tank Farms*, prepared by Kevin A. Lindsey, Daniel B. Stephens & Associates, and Kent D. Reynolds, Waste Management Northwest, for David A. Myers, TWRS Vadose Zone Program.

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APPENDIX A

GEOLOGY AND STRATIGRAPHY OF THE TANK FARMS

A1.0 INTRODUCTION AND PURPOSE

Vadose zone geologic data for Hanford Site single-shell tank (SST) farms are found in a variety of data sets, including borehole geologic logs, geophysical logs, particle size distribution databases, and hydrologic parameter databases. Vadose zone geologic data also are often portrayed on subsurface geologic maps and cross sections. The results of outcrops investigations of strata similar to those underlying the SST farms can provide additional information about vadose zone physical geologic conditions. Analysis of geologic information provides the basis for interpreting vadose zone physical geologic conditions and providing physical constraints for interpreting and modeling the three-dimensional flow and transport framework beneath the SST farms.

This appendix describes the data sources and derived geologic conceptual models of the geology underlying the SST farms. These models three goals:

- To provide a common basis for future SST farm vadose zone hydrogeologic investigations
- To provide a framework for interpreting general flow and transport conditions
- To aid in identifying the data needs for future SST farm vadose zone characterization.

To achieve these goals, this appendix identifies the types of vadose zone geologic data available for analysis, evaluates the applicability or use of these data for characterization activities, and identifies limitations in using the data sets to interpret subsurface conditions.

This appendix is divided into sections describing geologic data sets available for SST farm vadose zone geologic characterization (including their uses and limitations), large-scale geologic models for the SST farms based on the described data sets, and conclusions and recommendations relevant to SST farm geologic characterization. The following data sets relevant to SST farm geologic characterization are discussed:

- Borehole geologic logs (Section A2.2)
- Particle size distribution data (Section A2.3)
- Calcium carbonate content (Section A2.4)
- Borehole geophysical logs (Section A3.0)
- Geologic maps and cross sections (Section A4.0)
- Outcrop analogues (Section A5.0).

A2.0 BOREHOLE GEOLOGIC DATA

Geologic information used to interpret subsurface geology is gathered primarily from borings drilled for subsurface characterization and/or well emplacement. For Hanford Site SST farms, information collected from borings and used to interpret subsurface geologic conditions is found on borehole geologic logs, and in particle size distribution and calcium carbonate. Hydrologic parameter databases compiled from laboratory analysis of subsurface samples are discussed in Appendix B. Data collection objectives, sampling techniques, and geologic conditions affect the quality of these data sets to varying degrees. Consequently, the following discussion of borehole geologic data begins by reviewing drilling and borehole sampling factors that influence sample collection, quality, and suitability for analysis and interpretation. A discussion of the data found on borehole geologic logs and of data derived from the analysis of borehole geologic samples follows.

A2.1 DRILLING AND SAMPLING

Subsurface geologic conditions can be observed directly from samples (cores and cuttings) retrieved from boreholes. The quality and usefulness of these observations are directly influenced by the sample collection techniques used, borehole diameter, and borehole spacing. However, because drilling a boring every few feet or continuously collecting high quality samples to characterize subsurface conditions usually is not feasible or desirable, interpretations of subsurface geologic data should be made as technically defensible as possible. This is done by gathering accurate and representative data from samples collected using techniques that are compatible with the identified data needs and the subsurface conditions.

Reynolds and Lindsey (1994) summarize subsurface sampling factors that should be considered when analyzing borehole-derived geologic data collected at the Hanford Site. Tables in Reynolds and Lindsey (1994) list typical geologic parameters collected from subsurface samples. The tables also list drilling and sampling techniques that are both well suited and poorly suited for collecting the samples. Using these tables, or similar information found in characterization handbooks (for example see Sara [1994]), and American Society for Testing and Materials (ASTM) sampling and analysis protocols (for example, D5434-93; D2488-93; D4700-91; D1586-84; D1587-94; D2113-83), an investigator can determine with some degree of confidence whether borehole geologic data are accurate and representative of physical subsurface conditions in a given sample interval.

Reviewing subsurface geologic data applicable to SST farm vadose zone characterization with respect to drilling and sampling techniques reveals that, historically, data requirements have been subordinated by the available drilling and sampling techniques. The vast majority of the boreholes drilled in and around the SST farms have been drilled and sampled using cable-tool-driven-hard-tool, core-barrel, and split-spoon techniques. The following sections factor this information into discussions of the uses and limitations of the different borehole geologic data sets.

A2.2 BOREHOLE GEOLOGIC LOGS

Interpretations of subsurface geology at the Hanford Site are based predominantly on information found in borehole geologic, and to a lesser extent, geophysical logs. Logs exist for vadose zone borings and dry wells, groundwater monitoring wells, sediment core holes, and several types of geophysical tools.

A2.2.1 Vadose Zone Borings and Dry Wells

Geologic logs from vadose zone borings and dry wells form one of the largest geologic data sets used for interpreting physical geology beneath the Hanford Site SST farms. With few exceptions (for borings emplaced in the 1980's and 1990's), these logs are limited to the drillers log. Most of these logs have only generalized descriptions of subsurface geology. Examples of vadose zone and dry well geologic logs typical for SST farms include almost all the borings used for SST farm vadose zone radionuclide monitoring. Figures A-1 and A-2 illustrate the information content for most of these logs. That information is summarized as follows.

- Geologic descriptions on these logs concentrate on field estimates of gross particle size distribution (e.g., gravel, sand, silt) in a given interval and, less commonly, on color.
- These logs do not describe mineralogy, bedding characteristics, matrix content, and grain packing.
- Sampling and description intervals differ between logs. On some logs, described samples are not from discrete intervals in the boring, but are composites from some sampling interval. On others, a discrete sample from a specific depth may be described.
- Contacts between geologic units and lithologies, if reported, also differ between logs. Some logs show contacts to the nearest half foot; others give information only at 5-ft intervals.

Based on the types of information well geologic logs provide about the vadose zone, identifying geologic unit boundaries between Hanford formation subunits generally is possible. This is because these units are defined predominantly on the basis of dominant particle size distribution; information that is portrayed in general terms on most of the shallow boring and dry well logs. However, the lack of mineralogic and color information on these logs makes consistent, confident differentiation of the Hanford formation, Plio-Pleistocene unit (including silt and carbonate zones), and Ringold Formation difficult. Differentiating these units usually requires the use of mineralogy and color data in addition to particle size distribution data (Tallman et al. 1979, 1981; DOE 1988; Last et al. 1989; Reidel et al. 1992; Lindsey et al. 1994a; and Lindsey 1996). In addition, the lack of bedding, matrix, cement, and grain packing descriptions makes identifying and defining physical features for individual units, subunits, and lithologies that influence vadose zone hydrogeology difficult.

A2.2.2 Groundwater Monitoring Well Logs

Geologic logs from borings that penetrate into groundwater form a second geologic log data set for SST farms. Geologic logs from groundwater monitoring wells also vary in quality. Generally, older logs, from wells drilled before the early 1980's, contain less information than logs from later wells. For this discussion, monitoring well geologic logs relevant to SST farm characterization are divided into three general categories: older logs, intermediate logs, and recent logs.

A2.2.2.1 Older Logs. This set of logs was collected largely from monitoring wells drilled from the 1940's to as recently as the 1970's. Geologic logs prepared for older wells generally contain the same types of information as are found on most of the vadose zone and dry well geologic logs described in Section A2.2.1. The older monitoring well geologic logs have essentially the same uses and limitations as the vadose zone boring and dry well logs. Examples of the older monitoring well geologic logs can be found in appendices to numerous reports written for *Resource Conservation and Recovery Act of 1976 (RCRA)* and *Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA)* projects, Fecht and Lillie (1982), and on Figure A-3.

A2.2.2.2 Intermediate Logs. This subset of monitoring well logs typically was compiled from the mid 1970's to the early 1990's and prepared by well-site geologists. Many of these logs were prepared for wells drilled for RCRA and CERCLA projects and contain more information than the older monitoring well geologic logs. Examples of this subset of well logs are shown on Figures A-4 and A-5. The intermediate set of well logs includes the following information:

- Field estimates of particle size distribution range made by the well-site geologists. These estimates are visual approximations and are not based on sieve analysis.
- Color, which usually is described using Munsel color charts, although wet versus dry color is not consistently reported.
- Petrology of the sand and gravel size fraction, based on field identification of basic mineral and lithic types such as quartz, quartzite, basalt, volcanic rocks, feldspar, and mica.
- Calcium carbonate estimates based on the observed reaction of some part of the sample with dilute hydrochloric acid.

When reported accurately, this information is generally sufficient to identify all major geologic units and subunits in the Hanford formation, Plio-Pleistocene unit, and Ringold Formation. Although the data on these logs are more detailed than those found on vadose boring, dry well, and older monitoring well geologic logs, the following shortcomings limit their use for fully interpreting the characteristics of individual stratigraphic units, subunits, and lithologies.

- Data are not consistently reported on these logs. This lack of consistency limits the use of these logs for cross borehole correlation of specific lithologies, the interpretation of site-specific physical geology, and the identification of hydrologically important subunits and lithologies.
- Many of the samples described on logs are composites of drive barrel or cutting samples retrieved during drilling. Consequently, descriptions may represent averages between two or more unidentified lithologies.
- The mud content of individual samples is consistently recorded on these logs. However, many of these logs fail to describe whether the mud fraction occurred as matrix, interbeds, clasts in the sample, or was generated by the milling of samples during drilling. This information is needed to fully understand the influence of fines on vadose zone flow conditions.
- Field estimates of percent silt/clay fraction tend to be high in coarser, gravelly intervals because rock material is pulverized during drilling and sampling and analysts tend to overestimate fines content during visual examination. (See Lindsey [1996] for a discussion of this with respect to the Ringold Formation.) This inaccuracy can lead to an inability to identify strata with higher effective porosity than reported silt/clay contents suggest.
- Samples acquired from cemented, indurated, and gravel-rich intervals may not be representative of in situ, intact material. This observation is based on the presence of broken and angular rock fragments in "intact" sample descriptions.
- All samples collected and described in these logs are classified on the basis of the Folk particle size distribution classification system. This system does not account for mineralogy, matrix content, induration, and drilling effects on the physical sample. Consequently, sediment classifications given on these borehole logs generally do not record all the physical parameters that may control fluid migration.
- Most of these logs rigidly adhere to sample descriptions at 5-ft intervals, limiting recognition of lithologic variation and unit contacts.

A2.2.2.3 Recent Logs. In the early 1990's the quality of information recorded on some RCRA and CERCLA borehole geologic logs improved. These recent logs were prepared by geologists trained to recognize geologic features known to be present at the Hanford Site and to recognize the effects of drilling on samples. Where possible, given the range of geologic, drilling, and sampling factors affecting sample quality, geologists described the context of fine and coarse fractions, bedding, cement, grain packing, and the effects of drilling, in an effort to provide a level of detail needed to directly identify site-specific geologic conditions that may influence flow and transport. Most of the borehole logs collected during this period used interval logging methods that attempted to identify the precise depth of geologic features. Figures A-6 and A-7 are examples of these logs. Projects for which such logs were compiled include the following:

- Drilling for the CO18H project (Lindsey and Reidel 1992, Reidel and Thornton 1993), where attention was directed to the occurrence and thickness of calcium carbonate horizons. From these data, project geologists were able to identify that individual horizons were thin and lenticular.
- For the U-14 project examination of borehole samples revealed the presence of clastic dikes cross-cutting Plio-Pleistocene unit carbonate horizons and confirmed the limited lateral extent of silt-rich horizons in the vadose zone (Singleton and Lindsey 1994).
- Characterization efforts for the Environmental Restoration Disposal Facility (ERDF) led to the recognition of some of the more obvious effects of drilling. These include inadequate hole cleaning and the destruction of bedding/sample characteristics by the sampling methods. Observation and documentation of the drilling activities (circulation velocities, return volumes, blow counts, etc.) were shown to directly affect sample quality and characteristics, the ability to recognize clastic dikes known to be present throughout the vadose zone, and the context in which the mud fraction likely occurs (e.g., whether the mud fraction is present as a result of drilling actions or because of depositional mechanisms).
- RCRA monitoring well borehole geologic logs for the Low-Level Burial Grounds and the former Grout Treatment Facility typically recorded observations about bedding, matrix, grain packing, and cementation.

A2.2.3 Core Logs

Mud rotary rock core logs for 28 cored borings at the Hanford Site are described in Bjornstad (1984) and Lindsey (1996). These logs, examples of which are shown on Figure 8, describe the presence of many physical features not readily interpreted from most other borehole geologic logs, including interbedded lithologies, grain packing, cement, and matrix. However, because of the small number of core logs and their geographic distribution, their use is limited to 200 West Area SST farms from the top of the Plio-Pleistocene unit to groundwater. The small number of core logs in the 200 West Area (five total) also precludes the possibility of using them to describe and characterize the extent of individual zones or horizons that may affect vadose zone moisture and contaminant movement.

Given these limitations core logs can still be used to identify physical features relevant to flow and transport conditions, including the following:

- Cemented horizons in the Plio-Pleistocene unit and Ringold Formation
- The general lack of silt/clay matrix and the dominance of clast support in Ringold Formation gravel

- Interbedding of carbonate-rich and carbonate-poor lithologies in the Plio-Pleistocene unit.

Although the core logs are limited in number and can only be used to directly identify physical features controlling flow and transport at a given location, they can be utilized to infer conditions over larger areas using circumstantial evidence from other borings. By applying geologic observations from the few core holes to those on other geologic logs inferring probable physical geologic features that may influence vadose zone flow and transport beneath SST farms for units below the base of the Hanford formation is possible. This technique helps maximize the use of information on the other types of geologic logs.

A2.3 PARTICLE SIZE DISTRIBUTION DATA

Particle size distribution data form a large data set that can be used to supplement borehole geologic log interpretations. Particle size distribution data have been collected at the Hanford Site for many different projects. For the SST farms, particle size distribution data have been collected for all stratigraphic units and most have been compiled into a single database, ROCSAN. The ROCSAN database contains weight percent and cumulative weight percent distributions for nine particle size distribution categories (larger than fine pebble, fine pebble, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, silt, and smaller than silt). Samples are listed on ROCSAN by borehole and depth below surface. An example of a ROCSAN data entry is shown in Figure A-9. Geologic units are not identified, although the Price and Fecht (1976a-l) series of reports provides some stratigraphic subdivisions of vadose zone units based on these data. Additional particle size distribution data, generally for specific facilities and sites can be found in various RCRA and CERCLA reports.

Particle size distribution data provide a window into identifying stratigraphic units, lithologies, and physical properties present if investigators use it in conjunction with other data. Particle size distribution data can be used for the following types of subsurface geologic characterization:

- To identify lithologies present if relatively intact samples and bedding information can be collected.
- To identify stratigraphic units, if used in combination with mineralogy, color, and calcium carbonate data.
- To identify samples affected by drilling and sampling; these samples are inappropriate for analysis requiring intact samples.

To be used most effectively with other data, the limitations imposed on particle size distribution data by sampling techniques should be evaluated. Limitations in using particle size distribution data center on the following:

- As a function of data in particle size distribution databases are not qualified based on collection method, borehole conditions, or lithologic conditions.
- Some sampling events result in mixing of different lithologies during sample collection. Such samples should be used only for gross-scale particle size distribution range generalizations, and are not appropriate for identifying subsurface physical conditions.
- In borings where a small number of samples were collected, the samples may not be representative of an the entire unit.
- Driven split-spoon samples often result in breaking of gravel and lithified strata, rendering particle size distribution ranges partially reflective of drilling effects, not undisturbed material.
- Subsurface sampling at the Hanford Site generally has relied on the collection of 6-in.-long, 4-in.-diameter samples. These samples probably are not capable of representing of the range of particle size distributions present in gravel lithologies.

Based on these limitations, these data should not be used as the sole means or criterion for interpreting subsurface geologic conditions as commonly has been done.

A2.4 CARBONATE CONTENT

Calcium carbonate content is another common data set in Hanford Site geologic log files and reports applicable to SST farm geologic characterization. ROCSAN is the single largest data repository for this information (see Figure A-9). Also, like particle size distribution data, calcium carbonate data can be found scattered throughout numerous other reports, including those for CERCLA and RCRA projects.

As with other borehole geologic data, sampling factors must be evaluated before using calcium carbonate data. For CaCO_3 sampling, problems center on sampling intervals and bed thickness. Calcium carbonate in Hanford Site vadose zone sediments is disseminated throughout the zone, as nodules and as lenticular beds less than 1-ft thick. These zones or beds may be spaced several feet to many 10's of feet apart vertically (Reidel et al. 1992; Lindsey et al. 1994a, b; Slate 1996). Before the early 1990's, samples were collected at 5-ft. intervals, randomly, or not at all. Sampling was not directed to specifically identify CaCO_3 beds. Consequently the data show the following shortcomings.

- The sample spacing makes consistently identifying thin, widely spaced calcium carbonate-rich horizons typical of the Hanford vadose zone difficult to identify.
- Inconsistent application of 5-ft spacing has been seen where sampling may be done at the top, middle, or bottom of a 5-ft interval. In addition, some 5-ft samples also may be composites of either the preceding or succeeding 5-ft drilled interval.

- The geologic context of CaCO_3 in samples (e.g., disseminated, massive, lenticular, or nodular) is rarely reported.

A3.0 GEOPHYSICAL LOGGING DATA

Borehole geophysical logging has generated a significant data set from vadose, dry, and monitoring wells. Dry well logging with gross gamma detection systems was initiated for the tank farms in the 1960's. This logging was intended to detect changes in the levels of gamma-emitting nuclides above the set limit of 200 counts/second. The first data collected were presented only as analog strip charts; these were evaluated visually to determine if the recorded levels had a change greater than 200 counts/second above the original or baseline logs for the given well. After 1975, the system was updated to provide digital data collection and storage. However, this system was not intended, nor did it function as, a vadose zone evaluation tool because gradual low-level changes in the logs did not surpass the evaluation criteria. In 1998, Lockheed Martin Hanford Corporation (LMHC) began systematically reevaluating the historic data. The project has been completed for data gathered from the 241-SX SST farm between 1975 and 1994. These types of data sets, when compared to specific tank farm geologic conditions, have the potential to provide significant insight to contaminant movement mechanisms and lithologic influences at work beneath the tank farms.

RCRA and Operational Monitoring (ROM) activities also have led to the collection of geophysical logs for specific characterization efforts. Pacific Northwest National Laboratory operated this program from its inception until the late 1980's. Data gathered were in the form of paper copies of analog strip charts of gross gamma detections. Neutron logging tools also were deployed, but these were uncalibrated, which affected data consistency. Other difficulties associated with these logs include the following.

- Paper copies of the logs do not have consistent scale change notations. For example, peak count rate may exceed the range settings for the logged section or the operator changed the scale without noting it on the chart.
- Calibration efficiencies and repeatability for logging tools were insufficient to provide a high level of confidence
- No corrections for casing thickness or verification of signal/tool drift were applied to the data, reducing its usefulness and reliability.

Westinghouse Hanford Company (WHC) began systematic characterization logging efforts between 1989 and 1991 using high-resolution germanium logging tools and digital data storage systems. A similar effort performed through the U.S. Department of Energy, Grand Junction Projects Office (DOE-GJPO) to provide a baseline of spectral gamma information is nearing completion for all the SST farm dry wells. For wells where these systems were employed, the data sets are of high quality and are useful for identifying the specific gamma-emitting

radionuclides present. However, they are limited to lower concentrations of those radionuclides because of the high dead time at concentrations exceeding about 10,000 pCi/g.

For almost all of the geophysical logging undertaken to date at the Hanford Site, a number of problems consistently arise, including the following:

- Specific calibrations/correlations of tool responses to documented borehole conditions are not known for tools deployed before the early 1990's.
- No specific continuous cores or samples have been logged at the surface for comparison with the downhole responses, borehole-to-borehole correlation, and for identifying the character of tool responses to specific lithologies and geologic units.
- Only a few geophysical tools (primarily gamma and occasionally neutron) have been deployed on Site because of restrictions posed by drilling/construction conditions. This limited selection of tools does not provide sufficient information to quantify all the parameters required to specifically identify the subsurface units and lithologies.

A large amount of information is available mainly in the form of gamma logs, the more recent were acquired using sodium iodide detectors, which provide potassium, thorium, and uranium ratios (KUT) and spectral data, and high-purity germanium detectors, which provide state-of-the-art spectral detection of gamma-emitting radionuclides. These data are valuable and may be used in the context of understanding the depositional geologic framework. Understanding and geologic use of this data set would be well served by a systematic approach to characterizing the tool responses to outcrop and analog sections.

A4.0 GEOLOGIC MAPS AND CROSS SECTIONS

Geologic maps and cross sections that can be used for SST farm vadose zone geologic characterization are found in a variety of reports, including Price and Fecht (1976a-l), Last et al. (1989), Caggiano and Goodwin (1991), Lindsey et al. (1991, 1992, 1994a, and 1994b). The most common maps are isopach maps and structure contour maps, showing the thicknesses of units and the elevations of unit upper or lower bounding surfaces, respectively. Many of the reports containing subsurface geologic maps contain geologic cross sections.

The only comprehensive set of geologic cross sections specific to the vadose zone at all of the SST farms is found in Price and Fecht (1976a-l). However, because these cross sections are based only on particle size distribution data, they do not portray mappable stratigraphic units or provide insight into other lithologic factors that could influence vadose zone hydrology (e.g., grain packing, cement, matrix, and bedding). Other maps and cross sections may be of limited use for SST farm vadose characterization because detailed vadose zone geologic information is not given (Caggiano and Goodwin 1991), they are small in number (Johnson and Chou 1998), or they do not focus on the tank farms (Last et al. 1989, Lindsey et al. 1991, 1992, and 1994b).

With the following constraints, previously published maps and cross sections may be used to at least infer the presence of mappable geologic units beneath SST farms.

- All maps and cross sections are constructed from data in the various borehole geologic log data sets previously described. Consequently, the identified drawbacks associated with these logs will affect the interpretation of cross sections and maps prepared from the logs.
- Geologic maps and cross sections from different reports may not correlate directly. This occurs because stratigraphic nomenclature, definitions, and interpretations have changed over time.
- Maps and cross sections are themselves interpretations and conceptual models, and have to be viewed as such. Consequently, a user should be aware of the assumptions and generalizations that went into their preparation.
- Well spacing and map scales affect the interpretation of details portrayed on maps and cross sections. Therefore, many maps and cross sections covering areas around individual SST farms may provide only general geologic information about the facility.

A5.0 OUTCROP ANALYSIS AND ANALOGUES

Outcrop studies offer an opportunity to directly observe and analyze large- to small-scale physical geologic properties for specific geologic units, subunits, and lithologies. These observations and analytical data then can be applied to subsurface occurrences of similar units and lithologies. Correlating surface and subsurface analogues depends on identifying similar facies in outcrop, core, and cuttings using particle size distribution, mineralogy, bedding, color, geophysical properties, and geologic mapping. This practice is commonly used by geoscientists in the petroleum and coal industries for resource exploration, development, extraction, and modeling.

In sedimentary strata similar to those making up the Hanford Site vadose zone, facies can be defined to any level of detail desired to allow identification of physical features. A series of facies types common to most sediments has been defined by Miall (1978, 1985), Rust and Koster (1984), and Collinson (1986). These, or similar, classifications are used worldwide and are readily adaptable to local geologic conditions as shown in Lindsey (1996) for the Ringold Formation.

For the Hanford Site, several reports use outcrops and analogues to present general conclusions about subsurface physical conditions over large geographic areas (Reidel et al. 1992; Lindsey et al. 1994a, 1994b) or for specific geologic units (Lindsey 1996, Fecht et al. 1998). In a few cases, including the 216-U-14 ditch (Singleton and Lindsey 1994) and the C-108 project (Lindsey and Reidel 1992, Reidel and Thornton 1994), outcrop and analogue studies have been

limited to specific facilities or sites. Outcrop and analog studies for SST farm geologic interpretations are limited to general conclusions found in Lindsey and Law (1993).

A6.0 GEOLOGIC MODELS

Based on the previously described geologic data sets, four stratigraphic sequences have been prepared for Hanford Site SST farms. These models apply, one each, to the north and south halves of the 200 West and 200 East Areas.

A6.1 VADOSE ZONE GEOLOGIC UNITS

The main vadose zone stratigraphic units at Hanford Site SST farms are backfill; Hanford formation units H1, H1A, H2, H2A, and H3; the Plio-Pleistocene unit; and the Ringold Formation members of Wooded Island and Taylor Flat (Figure 10) (Myers et al. 1979; Tallman et al. 1979, 1981; PSPL 1982; Bjornstad 1984; Fecht et al. 1987; DOE 1988; Baker et al. 1991; Last et al. 1989; Smith et al. 1989; Delaney et al. 1991; Lindsey 1991, 1992, 1996; Lindsey et al. 1991, 1992, 1994a, 1994b; Reidel et al. 1992, 1994). These units provide the basic framework within which SST farm vadose zone geologic conditions can be interpreted. The general characteristics of these units are discussed in Sections A6.1.1 through A6.1.5.

A6.1.1 Backfill

Backfill is present at all SST farms. It ranges from coarse gravel to sand and silt and consists of sediment removed from and subsequently returned to tank farm excavations. SST farm backfill also could contain construction debris. The backfill was compacted at irregular intervals; it is hypothesized that this compaction might affect the vertical distribution of surface-spill contamination.

A6.1.2 Hanford Formation

The Hanford formation consists of uncemented gravel, sand, and silt deposited by Pleistocene cataclysmic flood waters (Fecht et al. 1987, DOE 1988, Baker et al. 1991). The Hanford formation is thickest in the central Hanford Site where it can be up to 107 m (350 ft) thick. It directly underlies backfill at all SST farms.

The Hanford formation is divided into three gross-scale facies (gravel-, sand-, and silt-dominated) that are gradational with each other (Baker et al. 1991; Reidel et al. 1992; Lindsey et al. 1994a, 1994b). General characteristics of the three facies are summarized as follows:

- **Silt-dominated facies.** This facies consists of interbedded, brown, tan, and buff, silt and fine- to coarse-grained felsic sand forming repeated, well stratified, lenticular to tabular, normally graded (fining upwards) beds less than 1 m (3 ft)

thick (Reidel et al. 1992; Lindsey et al. 1994a). Individual beds can be traced tens of meters across outcrops, but cannot be correlated between outcrops or from borehole to borehole. Calcium carbonate cemented horizons have been observed in some outcrops. This facies also is called slackwater deposits, Touchet Beds, and graded rhythmites (Myers et al. 1979; DOE 1988; Last et al. 1989; Baker et al. 1991). The presence of interbedded sand differentiates the silt-dominated facies from massive, unbedded loess and laminated silt deposits of the Plio-Pleistocene silt facies described in Section A6.1.3.

- **Sand-dominated facies.** Well-stratified, fine- to coarse-grained sand and granule gravel dominates the facies (Reidel et al. 1992; Lindsey et al. 1994a). Silt in the facies occurs predominantly as laterally discontinuous silt interbeds. Mineralogy ranges from felsic in silt and fine- to medium-sand to basaltic in coarse sand and granule gravel. Corresponding colors range from brown and tan to gray and black. Small pebbles and rip-up clasts may be present in addition to lenticular, pebble-gravel interbeds. In outcrop, the facies displays amalgamated, plane-bedded sand with intercalated silt lenses, and an open framework texture in the granule-rich sands. Deposits that make up this facies also have been called the laminated sand or transitional facies (Myers et al. 1979; DOE 1988; Last et al. 1989; Baker et al. 1991).
- **Gravel-dominated facies.** The gravel-dominated facies consists of cross-stratified, coarse-grained sand and granule-to-boulder gravel (Reidel et al. 1992; Lindsey et al. 1996). Intercalated, lenticular silt-rich horizons are found locally. Clast petrology ranges from felsic to basaltic, with basalt dominating beneath the 200 East and West Areas. Predominant colors are dark brown, gray, and black. The gravel-dominated facies can occur as isolated beds up to 2 m (6 ft) thick in other Hanford formation facies, as well as thick amalgamated gravel beds forming intervals up to 20 m (66 ft) thick. This facies is generally uncemented and matrix poor, displaying an open framework texture.

Beneath the 200 East and West Areas the Hanford formation is subdivided into several mappable units. The units, designated H1, H1A, H2, H2A, and H3, are defined on the basis of predominant facies described by Last et al. (1989), Lindsey et al. (1991, 1992, 1994a, 1994b), Lindsey and Law (1993), and Reidel et al. (1992).

- Units H1 and H3 are characterized by the predominance of the gravel-dominated facies. Units H1 and H3 generally are fine and thin to the south beneath the 200 East and West Areas and, where present, are found in the upper and lower parts of the Hanford formation, respectively. Intercalated strata of the sand-dominated facies occur locally in both units.
- At some locations, the upper part of unit H1 locally contains significant sand-dominated facies horizons and is designated unit H1A.

- A mix of the sand-dominated facies and silt-dominated facies characterizes unit H2. The relative proportions of each facies vary beneath the 200 Areas from more silt-dominated facies in the south to more sand-dominated in the north. Because of similar facies content, units H1 and H3 cannot be differentiated where unit H2 is absent.
- At some locations, unit H2 coarsens downwards into unit H3. Where this occurs, the transitional interval is designated unit H2A.

A6.1.3 Plio-Pleistocene Unit

A sequence of laterally discontinuous fluvial, alluvial, eolian, colluvial, pedogenic carbonate, and lacustrine deposits less than 12 m (40 ft) thick underlies the Hanford formation beneath 200 West Area SST farms (Myers et al. 1979; Tallman et al. 1979, 1981; DOE 1988; Reidel et al. 1992; Lindsey et al., 1994a, 1994b, Slate 1996). This layer is informally called the Plio-Pleistocene unit. The following facies are found in the Plio-Pleistocene unit.

- **Carbonate facies.** This facies (commonly called the “caliche” at the Hanford Site) consists of laterally discontinuous pedogenic and groundwater -derived, white, light gray, and light pink calcium carbonate. The calcium carbonate forms irregular partings, fracture fill, nodules, and horizons less than 30 cm (1 ft) thick. Where the facies is interstratified with the alluvial facies described in the following item, a complex sequence of discontinuous carbonate-rich and carbonate-poor strata are found. Commonly, the facies also is overprinted on underlying Ringold Formation strata. Where this occurs the facies will contain Ringold material.
- **Alluvial facies.** The alluvial facies consists of laterally discontinuous, interbedded reworked loess, basaltic sand and gravel, and mixed lithology quartzo-feldspathic sand and gravel. Calcium carbonate may be scattered throughout the facies. Southeast of the 200 East Area mixed lithology alluvial deposits of this facies are known as the pre-Missoula gravel (PSPL 1981). The alluvial facies also may be intercalated with the carbonate facies.
- **Silt facies.** Examination of cores drilled during the Basalt Waste Isolation Project (BWIP), outcrops of analogous strata, and drive barrel samples (Rohay et al. 1994, Singleton and Lindsey 1994; Lindsey et al. 1994a, 1994b) reveal that this facies consists of thin, planar laminated, tan and light brown fine sandy silt and massive, loess-like silt. Deposits forming the silt facies have been called the Early Palouse soil (Myers et al. 1979, Tallman et al. 1981, Bjornstad 1984, DOE 1988, Last et al. 1989, Lindsey et al. 1991).

Beneath the 200 West Area the Plio-Pleistocene unit can be divided into two subunits, an upper, silt facies-dominated interval and a lower, mixed carbonate and alluvial facies dominated interval.

A6.1.4 Ringold Formation

The Ringold Formation is up to 183 m (600 ft) thick beneath the Hanford Site. It consists of uncemented to locally well-cemented clay, silt, fine- to coarse-grained sand, and pebble to cobble gravel. Ringold sediments are predominantly felsic (Goodwin 1993, Lindsey 1996) and grouped into five facies associations defined on the basis of lithology, petrology, stratification, and pedogenic alteration (Lindsey 1991 1996, Lindsey et al. 1994a). Detailed descriptions of the facies associations—I - fluvial gravel, II - fluvial sand, III - overbank-paleosol silt, IV - lacustrine silt and sand, and V - basaltic alluvial sand and gravel—are found in Lindsey (1996).

The distribution of facies associations within the Ringold Formation forms the basis for its stratigraphic subdivisions (Lindsey 1996). The lower half of the Ringold Formation, informally called the member of Wooded Island, is subdivided into several subunits, designated A, B, C, D, and E, characterized by strata typical of the fluvial gravel and fluvial sand facies association. Units A, B, C, D, and E are separated by deposits of the overbank-paleosol and lacustrine facies association. The lowest of these fine-grained intervals is designated the lower mud unit. Interstratified deposits of the fluvial sand and overbank-paleosol facies association, informally called the member of Taylor Flat, and strata dominated by the lacustrine facies association, informally called the member of Savage Island, form the upper half of the Ringold Formation (commonly called the upper unit or upper Ringold).

Ringold strata in the vadose zone beneath the 200 West Area SST farms consist of a combination of unit E of the member of Wooded Island and the lowermost part of the member of Taylor Flat. Where Ringold Formation strata are found in the vadose zone beneath the 200 East Area SST farms, unit A and the lower mud unit of the member of Wooded Island are present.

A6.1.5 Clastic Dikes

Clastic dikes are found in the Hanford formation, as well as locally in other sedimentary units (Black 1979; Fecht and Weekes 1996; Fecht et al. 1998). Clastic dikes are vertical to subhorizontal fissures filled by multiple layers of unconsolidated sand, silt, clay, and minor gravel aligned parallel to subparallel to dike walls. Clastic dikes range vertically from 30 cm (1 ft) to 55 m (180 ft). In cross section, clastic dikes range from 1 mm to two m (6 ft) thick, and in plan view clastic dikes extend up to 100 m (328 ft) along strike. Clastic dikes form a branching pattern that in plan view forms polygons several tens of meters across. Where the dikes intersect the ground surface a feature known as patterned ground is observed. They are most abundant in Hanford formation sand-dominated and silt-dominated facies. Fecht et al. (1998) summarize the locations on the Hanford Site where clastic dikes have been identified. Clastic dikes are inferred to be present beneath all of the SST farms, and, at least locally, they cross cut the Plio-Pleistocene (Singleton and Lindsey 1994).

A6.2 TABLES

Tables A-1 through A-4 summarize information about the geologic units forming the vadose zone in each of the four gross scale model areas.

- Unit top elevations and thicknesses were compiled from borehole log data cross sections and maps in the Price and Fecht (1976a-l) series of reports, Caggiano and Goodwin (1991), Lindsey et al. (1994b). The wide range of values reflects natural variations as well as logging and sampling uncertainties.
- Percent-particle-size-distribution data were derived from the Price and Fecht (1976a-l) reports and the ROCSAN database. The data ranges reflect some combination of natural conditions and unquantified effects of the drilling and sampling methods used.
- Facies and lithology descriptions are summarized from unpublished field descriptions and published field descriptions (Reidel et al. 1992; Lindsey et al. 1994a; Lindsey 1996). They illustrate the general range of physical conditions present in each unit that may influence vadose zone conditions.

The hydraulic properties of the geologic units are discussed in Appendix B.

A6.3 GEOLOGIC CROSS SECTIONS

Four geologic cross sections, one for each modeled area described in Tables A-1 through A-4, accompany this report. See Figure A-11 for cross section locations. These cross sections portray the basic physical geology beneath each four area, and they graphically present much of the information found on Tables A-1 through A-4. In addition, annotation found on the cross sections highlight selected geologic features and conditions found in the units.

Figure A-12 is a north-south cross section through the area of the T series of SST farms. Figure A-13 is a north-south cross section from the U to the S-SX SST areas. The general geology of the B tank farms is portrayed on Figure A-14. Geologic units underlying the C and A-AX SST farms are illustrated on Figure A-15.

A7.0 SUMMARY

Geologic data sets, including geologic and geophysical borehole logs, particle size distribution, and calcium carbonate content can be used to interpret the presence and extent of mappable geologic units beneath the SST farms. Previously published maps and cross sections provide additional, generalized information about the presence and extent of these geologic units beneath the SST farms. The vadose zone beneath the SST farms is contained in the Hanford formation, Plio-Pleistocene unit, and Ringold Formation. However, the thicknesses of these units and specific facies present differ between tank farms (see Tables A-1 through A-4).

Beneath 200 West Area tank farms (241-S, -SX, -T, -TX, -TY, and -U) all three units are present. In the northern part of the 200 West Area, in the area of the T tank farms:

- Hanford formation strata are dominated by gravel-dominated and sand-dominated facies divided into an upper gravelly unit (H1) and a lower sandy unit (H2). The Hanford formation generally fines and bedding thicknesses decrease to the south.
- The Plio-Pleistocene unit consists of a mixed, interbedded sequence of silt, carbonate, and alluvial sand and gravel facies divided into an upper silt-rich interval and a lower, mixed carbonate and alluvial interval.
- Indurated Ringold Formation gravel, sand, and silt extend as much as 30 m (98 ft) above the water table, with the thickness of the Ringold Formation above groundwater increasing to the north.
- Clastic dikes are inferred to be present in the Hanford formation and to cross cut the Plio-Pleistocene unit.

To the south, beneath the S and SX tank farms

- The base of the Hanford formation is as much as 49 m (160 ft) below ground surface and intercalated silt-dominated facies becomes more abundant and gravelly facies thin
- The Plio-Pleistocene unit thins and the carbonate facies may be locally absent
- As little as 8 m (26 ft) of indurated Ringold Formation is found above the water table
- Clastic dikes are inferred to be present in the Hanford formation and to cross cut the Plio-Pleistocene unit.

The vadose zone beneath 200 East Area tank farms (241-A, -AX, -B, -BX, -BY, and -C) is located almost completely in the Hanford formation. Beneath the 200 East Area tank farms

- The sand-dominated facies characterized by coarse-grained sand and local interbedded silt and gravel is the predominant lithology in the Hanford formation and forms unit H2. This unit generally thickens and fines towards the south-southwest.
- Gravel-dominated facies are found, but they are more common to the north where unit H1 and unit H3 thicken and where many gravel interbeds are found in unit H2
- Clastic dikes are inferred to completely cross cut the Hanford formation

- The top of the Ringold Formation typically is found near the water table at the A SST farms. Beneath part of the B tank farms, the Ringold Formation is absent and the Hanford formation directly overlies basalt. At the C farm, the top of the Ringold Formation currently lies below the water table.

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Table A-1. Compilation of Geologic Properties for Units underlying the Area of the 241-T, -TX, and TY Tank Farms. (2 sheets)

Unit	Top elevation (ft)	Thickness (ft)	%gravel	%sand	%z/c	Facies/Lithology
Eo ¹	672-670 (where present)	0-10				
BF	672-670	0-50	35-55	40-55	5-15	Reworked, massive to bedded, variably compacted silt, sand, and gravel containing construction debris
H1	672-620 (where present)	0-40 ²	10-20	80-90	<5-10	Uncemented pebble-cobble gravel with coarse sand to open-framework matrix; silt content usually as clast coatings or as thin, discontinuous interbeds; beds laterally discontinuous; bedding thins and unit fines towards south
H2	622-610	15-55 ³	0-5	55-95	<5-45	Uncemented, well stratified, laterally discontinuous beds of fine to coarse sand; lenticular CaCO ₃ and silt-rich beds may be present; bedding thins and unit fines towards south
PPz	590-570 (where present)	0-15	0	35-75	25-65	Massive to thinly bedded, uncemented silt and minor very fine sand
PPc	585-550	5-20	NA ⁴	NA ⁴	NA ⁴	Variably bedded and indurated silt, sand, and gravel; carbonate layers very discontinuous
Ru	570-530 (where present)	0-25	0-5	35-85	10-65	Variably interbedded silt and fine to coarse sand
RE	552-512 ft	70-100	64-88	12-36	0-5	Variably indurated pebble-cobble gravel with fine to coarse sand matrix; cemented zones occur as lenticular layers and zones; minor lenticular silt interbeds present

1 - Never present within tank farm boundaries

2 - Thins towards south

3 - Thickens towards south

4 - Not calculated because calcium carbonate cementing grains together will lead to inaccurate measurement of particle size distribution range.

Table A-2. Compilation of Geologic Properties for Units underlying the Area of the 241-S, and -SX Tank Farms. (2 sheets)

Unit	Top Elev.	Thickness	%gr	%sand	%z/c	Facies/Lithology
EO	660-667	0-10				
BF	660-667	0-53	5-40	55-90	5-15	Reworked, massive to bedded, variably compacted silt, sand, and gravel containing construction debris
H1A	667-609 (where present)	0-65 ¹	0-15	70-95	5-30	Uncemented, lenticular bedded; fine to coarse sand with intercalated gravel beds; unit coarsens to north, fines to south
H1	660-585 (where present)	0-40 ²	5-65	30-85	5-20	Uncemented, lenticular bedded, pebble-cobble gravel; coarse sand to open framework matrix; silt generally found as clast coatings and thin, lenticular interbeds; unit fines and bedding thins to south
H2	625-560	30-120 ³	0-10	65-85	0-35	Uncemented, lenticular bedded, interbedded fine to coarse sand and silt; lenticular CaCO ₃ -rich beds may be present locally; unit fines and beds thin to south
H3	580-530 (where present)	0-50	10-40	50-70	5-35	Uncemented, interbedded lenses of sand and gravel; generally fines downwards; irregular distribution
PPz	545-495 (where present)	0-35	0	50-65	35-50	Massive to bedded, uncemented silt and sandy silt
PPc	530-495 (where present)	0-20	NA ⁶	NA ⁶	NA ⁶	Lenticular, variably bedded and indurated, interbedded silt, sand, and gravel cemented with variable amounts of calcium carbonate
Ru	520-495 (where present)	0-10	0-5	80-95	5-20	Variably interbedded, lenticular silt and fine to coarse sand
RE	525-485	25-45 ⁵	64-88	12-36	0-3	Variably indurated pebble-cobble gravel with fine to coarse sand matrix; cemented zones occur as lenticular layers and zones; minor lenticular silt interbeds present

1 - Thins to north and beneath SST farm excavations.

2 - Thins to south and beneath SST farm excavations.

3 - Generally thickens to south, except where gravelly strata assigned to unit H3 are present, at these locations H2 thins.

4 - Not calculated because calcium carbonate cementing grains together will lead to inaccurate measurement of particle size distribution range.

5 - Thickness above water table

Table A-3. Compilation of Geologic Properties for Units underlying the Area of the 241-B, -BX, and -BY Tank Farms. (2 sheets)

Unit	Top Elev.	Thickness	%gr	%sand	%z/c	Facies/Lithology
BF	650-660	0-49	20-50	40-70	5-10	Reworked, massive to bedded, variably compacted silt, sand, and gravel containing construction debris
H1 ¹	660-661 (where present)	0-55 ²	10-40 ³	55-85 ³	5-15 ³	Uncemented, lenticular bedded, pebble to cobble (locally boulders) gravel; coarse sand to open framework matrix; silt present as clast coatings and as thin, lenticular interbeds; unit fines and bed thins to south
H2	620-575	95-200 ³	<5-10 ³	80-95 ³	5-15 ³	Uncemented, lenticular bedded, fine to coarse, locally pebbly, sand; fine beds present locally; unit fines and beds thin to south
H3	500-405	5-90 ⁴	10-40	55-85	5-15	Uncemented, lenticular bedded, pebble to cobble (locally boulders) gravel; coarse sand to open framework matrix; silt present as clast coatings and as thin, lenticular interbeds; unit fines and bed thins to south
RLM	430-440 (where present)	0-30	NA ⁶	NA ⁶	NA ⁶	Massive to thinly bedded silt with minor sand; well compacted
RA	405-415 (where present)	0-30	64-88 ⁷	12-36 ⁷	0-3 ⁷	Variably indurated pebble-cobble gravel with fine to coarse sand matrix; cemented zones occur as lenticular layers and zones; minor lenticular silt interbeds present

1 - Includes unit H1a which is only locally present.

2 - Thins to south

3 - Generally thickens to south.

4 - Thickens and thins irregularly.

5 - Fines generally to south.

6 - Not available, but generally will be extremely silt/clay rich (Lindsey, 1996).

7 - Compiled from same borings used for RE on Tables 1 and 2.

Table A-4. Compilation of Geologic Properties for Units underlying the Area of the 241-A, -AX, and -C Tank Farms. (2 sheets)

Unit	Top elevation (ft)	Thickness (ft)	%gravel	%sand	%s/c	Facies/Lithology
EO	695-650 (where present)	0-15				
BF	688-650 (where present)	0-55	5-60	40-80	<5-15	
H1	680-610 (where present)	0-70 ¹	10-70 ³	25-80 ⁵	<5-10 ⁵	Uncemented, lenticular bedded, pebble to cobble (locally boulders) gravel; coarse sand to open framework matrix; silt present as clast coatings and as thin, lenticular interbeds; unit fines and bed thins to south
H2	615-580	120-200	1-10 ⁶	55-95 ⁶	<5-35 ⁶	Uncemented, lenticular bedded, fine to coarse, locally pebbly, sand; fine beds present locally; unit fines and beds thin to south
H3	490-430 (where present)	0-70 ²	10-70 ³	25-80 ⁵	1-10 ⁵	Uncemented, lenticular bedded, pebble to cobble (locally boulders) gravel; coarse sand to open framework matrix; silt present as clast coatings and as thin, lenticular interbeds; unit fines and bed thins to south
RLM	425-410 (where present)	0-30 ³	NA ⁷	NA ⁷	NA ⁷	Massive to thinly bedded silt with minor sand; well compacted
RA	425-395	<20 ⁴	64-88 ¹²	12-36 ¹²	0-5 ¹²	Variably indurated pebble-cobble gravel with fine to coarse sand matrix; cemented zones occur as lenticular layers and zones; minor lenticular silt interbeds present

1 - Thins to west and east.

2 - Thins to south, southwest, and southeast.

3 - Probably thickens and generally dips to south.

4 - Thickness above ground water.

5 - Fines to south.

6 - Coarsens to north grading into gravel.

7 - Not available, but generally will be extremely silt/clay rich (Lindsey, 1996).

Figure A-1. Example of a Vadose Zone Boring and Drywell Geologic Log,
Borehole 299-W-23-4, Depth 35 to 65 ft.

DRILLING LOG									
RIG NO.		WELL NO.		DATE		PROJECT NO.		DEPTH BEGINNING OF SHIFT	
A.E.C. 22-3128		299-W23-4		May 27, 1957				30'	
DRILLER		FOREMAN		SHIFT				DEPTH COMPLETION OF SHIFT	
								69'	
DRILLING		CORING		TYPE SOIL		TIME		OTHER DELAYS	
TIME	DEPTH	TIME	DEPTH					EXPLANATION	
0730-1000	35'			Cobbles-gravel					
1000-1130	40'			Coarse gravel and sand					
1200-1230	45'			Sand-silt-little gravel		1130-1200		Welding 7'1" pipe (44'7" OH)	
1230-1300	50'			Sand-silt-little gravel					
1330-1430	55'			Sand-little silt		1300-1330		Welding 9'10" pipe (54'5" OH)	
1430-1500	60'			Sand-little silt					
1530-1545	65'			Sand-little silt		1500-1530		Welding 11'1" pipe (65'6" OH)	
REMARKS									
800 count at 40'									
600 count at 45'									
250 count at 50'									
200 count at 65'.									

W-1731- / 843 sec-se micellar. water.

Figure A-2. Example of a Vadose Zone Boring and Dry Well Geologic Log,
Borehole 299-E27-65, Depth 42 ft, 10 in. to 84 ft, 8 in.

DRILLING LOG									
RIG NUMBER 1#	WELL NUMBER E27-65	DATE 12-18-72	PROJECT NUMBER	DEPTH BEGINNING OF SHIFT 40	DEPTH COMPLETION OF SHIFT 85	OTHER DELAYS	EXPLANATION	TIME	TYPE SOIL
TIME	DEPTH	TIME	DEPTH	TIME	DEPTH	TIME	DEPTH	TIME	DEPTH
9:15-9:40	42' 10"	9:40-10:15	40-45	8:30-9:15	40-45		hauling sample jars & starting machines		coarse sand
10:30-11:00	53' 6"	10:15-10:30	45-50	11:30-12:30	45-50		Lunch		coarse sand & pea gravel
12:30-1:30	64' 2"	11:00-11:15	50-55	3:50-4:30	50-55		Cutting & trying to weld casing. Raining to hard.		coarse sand & pea gravel
2:25-2:40	74' 5"	11:15-11:30	55-60		55-60				medium sand
	84' 8"	12:30-1:00	60-64		60-64				medium sand
		1:30-1:40	64-65		64-65				medium sand
		1:40-2:00	65-70		65-70				medium sand
		2:00-2:25	70-75		70-75				medium sand
		2:40-3:20	75-80		75-80				medium sand
		3:20-3:50	80-85		80-85				medium sand
REMARKS									
Samples @ 45, 50, 55, 60, 65, 70, 75, 80, and 85									

2-7-102 (P-70) 4144 01/10/80, 840

Figure A-3. Example of an Older Groundwater Well Geologic Log, Borehole 299-E33-10, Depth 185 to 215 ft.

[illegible]

Figure A-4. Example of an Intermediate Groundwater Well Geologic Log, Borehole 299-E25-38, Depth 37 to 50 ft.

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DRILL LOG		Fig. 2-11103 BE-60L LOGS	Well Number 299-E25-38 Depth 37 to 50	Computer Number NA	Project or Work Order No. 1-017	Subcontractor NA
Total Casing	Depth	Drill Method	Wet/Dry Sample	LITHOLOGIC DESCRIPTION % Each Grain Size, Color, Roundness, Calcite, Etc.	Time	Drilling Comments
	40'	barrel	dry	MEDIUM SAND, 5% silt, 15% fs, 35% ms, 30% cs, 10% ves, 5% small pebbles, mostly angular basaltic, color 10YR 3/2 very dark grayish brown, unconsolidated, slight rxn in 10% HCl Added 9' 05" casing	0805	2 pint jar sample 1 moisture sample 1 chemical sample
49 1/2'	45'	core barrel	dry	MEDIUM SAND, 5% silt, 20% fs, 45% ms, 25% cs, 5% ves, mostly angular basaltic, color 10YR 3/2 very dark grayish brown, unconsolidated, moderate rxn in 10% HCl	1000	2 pint jar sample 1 moisture sample
	50'	core barrel	dry	MEDIUM SAND, 5% silt, 20% fs, 40% ms, 25% cs, 5% ves, 5% pebbles mostly angular basaltic sand, pebbles are rounded Basaltic, color 10YR 3/2 very dark grayish brown, unconsolidated, no rxn in 10% HCl Added 10 1/4' of 10" casing	1050	2 pint jar sample 1 moisture sample
10 1/4'						
59 1/2'					1100	

REMARKS:

6/9/89

A-1000-021 (4-88)

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Figure A-6. Example of a Recent Groundwater Well Geologic Log,
Borehole 299-W26-10, Depth 60 to 80 ft.

BOREHOLE LOG				Boring or Well No. <u>299-W26-10</u>	
				Sheet <u>4</u> of <u> </u>	
Location <u>S-10 ditch south of 200 W</u>		Project <u>S-10 ditch</u>			
Elevation <u> </u>		Drilling Contractor <u>Kaiser Engineers Hanford</u>			
Driller <u>McI Thorson</u>		Drilling Method and Equipment <u>Cable Tool</u>			
Prepared By <u> </u> (Sign/Print Name)		Date <u> </u>		Reviewed By <u> </u> (Sign/Print Name) Date <u>2/4/91</u>	
Depth	Sample Type and No.	Blows or Recovery	Graphic Log	Sample Description	Comments
60'	2 1/4" 1 moist 1 rad	DB		(60') slightly silty SAND (10% silt 90% sand) MS-10% FS-40% VFS-40% silt 2.5-4 1/2 yellowish brown, damp and compactable, 60% mica 40% f.lite mod. 10% HCL rxn mica flakes present (62') sandy Silt loam (70% silt 30% sand) 2" thick	2/26/91 10" CS casing cd 2 59' surveyed clean w/ SIP more moisture present four sand
65'	2 1/4" 1 moist 1 rad	DB		(65') slightly silty sandy GRAVEL (10% silt 40% gravel 50% sand) gravel SC-10% KP-15% CP-5% MP-5% FP-5% sand MS-10% FS-20% VFS-20% silt 2.5-4 1/2 yellowish brown, damp 60% mica 40% f.lite, mod. 10% HCL rxn mica flakes present	2/26/91 10" CS casing cd 2 61' surveyed clean w/ SIP
68'	2 1/4" 1 moist 1 rad	DB		(68') silty sandy GRAVEL (25% silt 30% gravel) 55% sand, damp, mod. 10% HCL rxn gravel SC-10% CP-10% MP-5% FP-5% (70') sand MS-10% FS-20% VFS-25% silt 2.5-4 1/2 yellowish brown 60% mica 40% f.lite mica flakes present	2/26/91 10" CS casing cd 2 65' surveyed clean w/ SIP and darker in color
70'	2 1/4" 1 moist 1 rad	DB		(70') slightly silty SAND (10% silt 90% sand) MS-10% FS-40% VFS-40% silt 2.5-4 1/2 yellowish brown, damp 60% mica 40% f.lite, mod. 10% HCL rxn mica flakes present gravel starts @ ~72.5'	had slow drilling 4 cuttings becoming more silty 2/27/91 10" CS casing cd 2 65' surveyed clean w/ SIP
75'	2 1/4" 1 moist 1 rad	DB		(75') slightly silty sandy GRAVEL (10% silt 50% gravel 40% sand) gravel SC-20% CP-15% MP-10% FP-5% sand MS-15% FS-15% VFS-10% silt 2.5-4 1/2 yellowish brown, damp 60% mica 40% f.lite mod. 10% HCL rxn mica flakes present gravel ends @ ~79.5'	2/27/91 10" CS casing cd 2 69' surveyed clean w/ SIP & det very hard drilling, CB is getting choked up may have to go to HT 1 large rounded cobble found at 76'
80'					

A-6000-382 (04/90)

Figure A-7. Example of a Recent Groundwater Well Geologic Log, Borehole 299-W23-16, Depth 140 to 160 ft.

BOREHOLE LOG				Boring or Well No. <u>299-W23-16</u>	
				Sheet <u>8</u> of <u> </u>	
Location <u>216-4-14 200 WEST</u>			Project <u>RCRA - W0152</u>		
Prepared By <u>James J. Anderson</u> Date <u>4/27/93</u>			Reviewed By <u> </u> Date <u> </u>		
(Sign/Print Name)			(Sign/Print Name)		
Depth	Sample	Graphic Log	Sample Description	Comments	
(146)	Type and No.	Blows or Recovery	Group Name, Group Symbol, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Depth of Casing, Drilling Rate, Casing Size & Type, Bit Size, Water Level	
146	211H 146H 146H	DB	146' sample 4/27/93 @ 146' 20% silt, 80% SAND material dsl some as above w/ good sorting 2.5 y 4/3 Holbrn - olbrn - wet 2.5 y 3/3 Holbrn - slightly moist sub eng - eng SAND up in dsl TANUS are present. 10% left remaining best minor musc, west Rm to 10% HCl > 2% staining in horizontal & vertical beds @ 143.5'	146' sample 4/27/93 @ 146' ARC @ 137.5' BSS No det 4/ field inst ARC recovery 4/ combined 4/27/93 2 y 1/2 H2O added for rec 4/27/93 145' sample 4/27/93 @ 143.5'	
145	211H 145H 145H	DB	silt stinger (horizontal) - 144.4' - 144.9' BSS silt SAND - m.s. - 20% silt 70% SAND 40% fs 60% vs - obs 2.5 y 4/2.5 gray brn - 140 brn - wet 2.5 y 4/2 brn gray - dry, sample moist very good sorting, sub eng predom 0/2 w/ brn @ 20% and musc @ 10% west Rm to 10% HCl	145' sample 4/27/93 @ 143.5' No det 4/ field inst ARC @ 143.7' No H2O added musc - 0/3 stinger @ ~ 147' 4/ > moisture 150' @ 112.0 4-10-93 146' H2O @ 147' - 149' > moisture musc - 0/3 stinger @ ~ 147.5' 4/ > moisture also @ 149.5' > moisture possible H2O bearing zone 147' - 149' 149' - 152' 1/2 brn - wet @ 152'	
150	211H 150H 150H	DB	slow recovery silt SAND - m.s. - 20% silt 80% SAND 20% fs - 70% vs - coarse in dsl area obs 2.5 y 4/2.5 gray brn - Holbrn - wet mixing some chg in dsl to 10% 4/3 pl brn - wet @ 152'	slow recovery also @ 149.5' > moisture possible H2O bearing zone 147' - 149' 149' - 152' 1/2 brn - wet @ 152'	
152	211H 152H 152H	DB	2.5 y 4/2 dry, sample slightly moist very good sorting, sub eng, predom 0/2 - 0/2 w/ 20% brn - wet 153.0 - 153.7 sample from core barrel shows plastic-like interlocking colicic zone - w/ silt stinger below	152' sample 4/27/93 @ 152' 153.0 - 153.7 sample from core barrel shows plastic-like interlocking colicic zone - w/ silt stinger below	
154	211H 154H 154H	DB	154.1 - 155.6' - slightly sandy GRAVEL 4/3 bag colicic 20% sand 80% GRAVEL obs - some as above except for fragmented colicic - 10% 4/3 pl brn - wet good sorting, moist sample, grains are red-mottled, sand are sub eng strong Rm to 10% HCl	154' sample 4/27/93 @ 154' 154.1 - 155.6' - slightly sandy GRAVEL 4/3 bag colicic 20% sand 80% GRAVEL obs - some as above except for fragmented colicic - 10% 4/3 pl brn - wet good sorting, moist sample, grains are red-mottled, sand are sub eng strong Rm to 10% HCl 154' @ 150.0 4/27/93	
155	211H 155H 155H	DB			
156	211H 156H 156H	DB			

A-6000-382 (01/93)

Figure A-8. Example of a Core Log from Lindsey (1996),
Borehole 299-W11-26 (DH-6), Depth 90 to 310 ft.

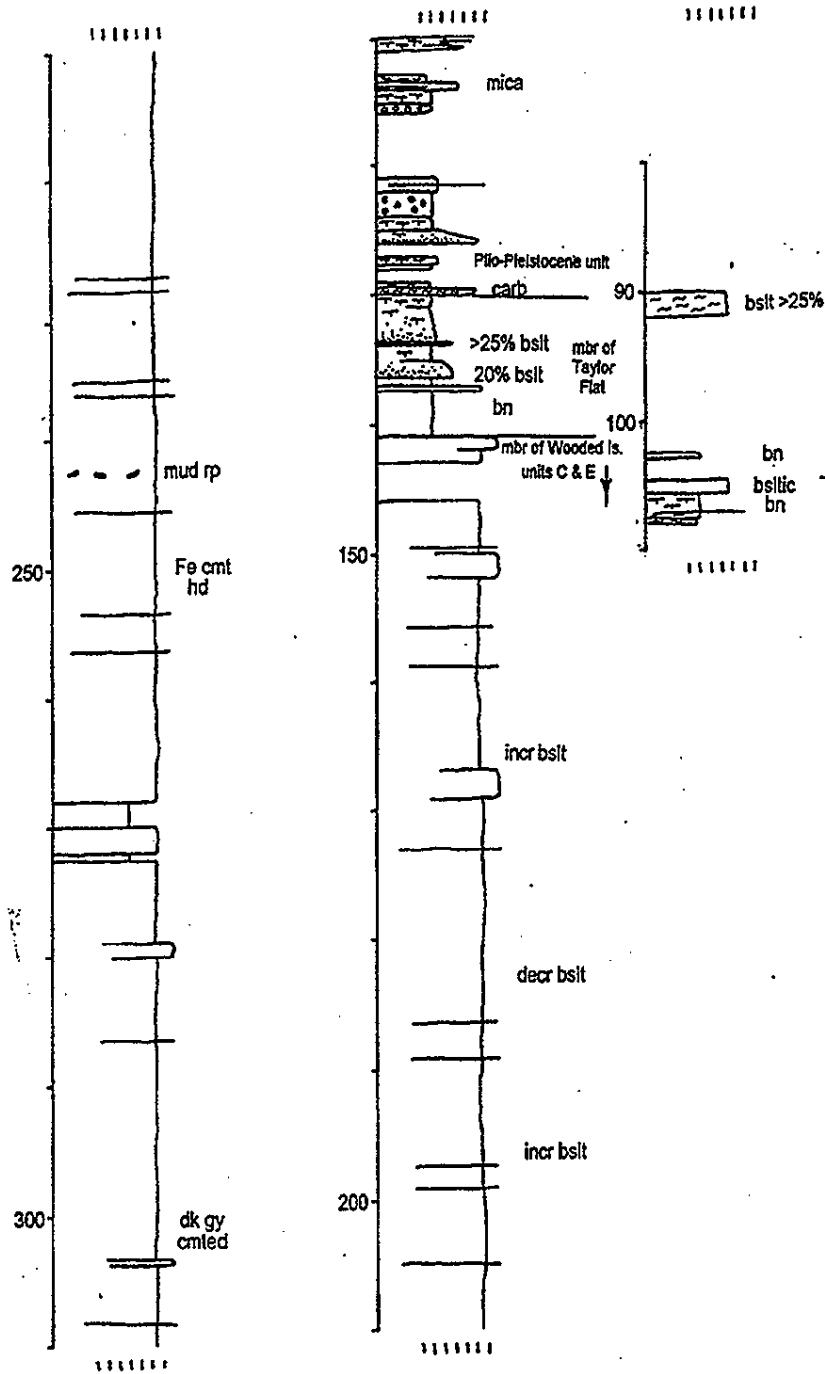


Figure A-9. Copy of a Page from the Rocsan Database Showing the Types of Information Contained Within the Database.

06/30/89

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**** REPORT ON WELL 0290-E33-084 ****

DEPTH	XCARC03	DM	XSD	XSRND	XGRAVEL	CLASS	FINE PES (-2)	VFINE PES (-1)	VERY COARS (0)	COARS (1)	MED (2)	FINE (3)	VERY FINE (4)	SILT (4.75)	PAH (4.75)
5	0.5 C	17.7	51.3	20.9	gms		14.8	19.1	24.7	31.1	18.8	13.0	11.9	10.4	18.4
SORT=	2.81	MEDIAN=	1.00	MODE=	1.00	PERN=	9.2	11.8	15.2	19.2	11.8	8.0	7.3	6.4	11.3
SPLIT	183.0						CUM	9.2	20.9	36.1	55.3	66.9	74.9	88.7	100.0
10	0.8 C	11.9	45.5	41.5	ms		41.8	21.3	18.6	20.5	14.3	9.3	7.9	6.4	11.7
SORT=	N/A	MEDIAN=	0.00	MODE=	-2.00	PERN=	27.5	14.0	12.3	13.5	9.4	6.1	5.2	4.2	7.7
SPLIT	152.4						CUM	27.5	41.8	53.8	67.3	78.7	82.9	98.1	100.0
15	0.8 C	11.9	49.2	38.8	ms		24.6	35.4	26.7	20.4	12.5	9.5	6.9	6.2	12.2
SORT=	2.54	MEDIAN=	0.00	MODE=	-1.00	PERN=	15.9	22.9	17.3	13.2	8.7	5.5	4.5	4.0	7.9
SPLIT	155.1						CUM	15.9	28.9	56.2	69.4	78.1	83.6	98.1	100.0
20	0.7 C	20.0	42.4	37.7	ms		47.6	16.2	15.9	15.3	11.9	10.6	18.1	16.5	17.3
SORT=	N/A	MEDIAN=	1.00	MODE=	-2.00	PERN=	28.1	9.8	9.4	9.0	7.0	6.3	10.7	9.7	10.2
SPLIT	169.5						CUM	28.1	37.7	47.1	56.1	63.1	69.4	80.0	100.0
30	0.6 C	17.3	58.1	24.8	gms		19.4	21.0	18.7	24.4	21.6	15.9	14.7	11.5	16.8
SORT=	2.90	MEDIAN=	1.00	MODE=	1.00	PERN=	11.8	12.8	11.4	14.8	13.2	9.7	9.0	7.0	10.2
SPLIT	185.0						CUM	11.8	24.8	36.0	50.9	64.1	73.8	82.7	99.8
35	0.8 C	16.4	82.3	21.3	gms		15.2	20.5	33.9	31.5	15.5	10.8	12.9	11.3	16.2
SORT=	2.73	MEDIAN=	1.00	MODE=	0.00	PERN=	9.1	12.2	20.2	18.8	9.2	6.4	7.7	6.7	9.7
SPLIT	188.3						CUM	9.1	21.3	41.5	60.3	69.5	75.9	83.6	100.0
40	1.0 C	17.7	68.7	13.6	gms		3.9	17.8	30.6	32.7	18.9	14.2	12.4	10.5	17.8
SORT=	2.53	MEDIAN=	1.00	MODE=	1.00	PERN=	2.4	11.1	19.2	20.5	12.5	8.9	7.8	6.6	11.1
SPLIT	160.5						CUM	2.4	13.6	32.7	53.2	65.6	74.5	82.3	100.0
50	0.6 C	18.7	68.1	13.2	gms		5.1	15.8	28.5	31.2	21.1	14.9	10.8	10.8	18.8
SORT=	2.55	MEDIAN=	2.00	MODE=	1.00	PERN=	3.2	9.9	16.9	19.9	13.4	9.5	8.5	6.3	11.8
SPLIT	157.7						CUM	3.2	13.2	30.0	49.9	63.3	72.8	81.3	100.0
60	0.8 C	14.4	74.9	10.7	(m)S		2.5	12.1	34.4	34.8	17.0	9.8	6.2	5.3	14.3
SORT=	2.21	MEDIAN=	1.00	MODE=	1.00	PERN=	1.8	8.9	25.2	25.5	12.5	7.2	4.6	3.9	10.5
SPLIT	136.5						CUM	1.8	10.7	35.9	61.4	73.9	81.1	85.6	100.0
65	1.5 C	15.1	81.0	3.8	(m)S		0.7	5.4	30.0	55.1	20.7	12.1	7.9	6.5	16.9
SORT=	2.10	MEDIAN=	1.00	MODE=	1.00	PERN=	0.5	3.5	19.3	35.5	13.3	7.8	5.1	4.2	10.9
SPLIT	157.0						CUM	0.5	3.9	23.3	58.7	72.1	79.9	84.9	100.0
75	1.4 C	13.0	85.4	1.6	(m)S		0.2	1.9	22.7	54.0	20.7	10.8	7.0	5.3	12.2
SORT=	1.78	MEDIAN=	1.00	MODE=	1.00	PERN=	0.2	1.4	18.9	40.1	15.4	7.9	5.2	3.9	9.1
SPLIT	134.9						CUM	0.2	1.6	18.4	58.5	73.9	81.8	87.0	100.0
80	1.1 C	2.6	96.6	0.6	S		0.0	0.8	25.1	70.2	23.7	10.5	5.2	1.7	1.9
SORT=	1.01	MEDIAN=	1.00	MODE=	1.00	PERN=	0.0	0.8	18.0	50.5	17.0	7.6	3.7	1.2	1.4
SPLIT	140.1						CUM	0.0	0.6	18.6	69.1	86.1	93.7	97.4	100.0
85	1.5 C	16.5	82.6	0.9	(m)S		0.0	1.3	31.7	54.3	17.4	10.9	8.7	6.7	17.8
SORT=	2.19	MEDIAN=	1.00	MODE=	1.00	PERN=	0.0	0.9	21.3	35.5	11.7	7.3	5.8	4.5	12.9
SPLIT	149.8						CUM	0.0	0.9	22.2	58.6	70.3	77.6	83.5	100.0
95	1.1 C	10.4	85.9	3.7	(m)S		0.8	5.4	28.6	62.3	30.5	11.8	8.7	5.3	11.6
SORT=	1.54	MEDIAN=	1.00	MODE=	1.00	PERN=	0.4	3.3	17.6	38.3	18.7	7.3	4.1	3.3	7.1
SPLIT	163.0						CUM	0.4	3.7	21.3	59.5	78.3	85.5	89.6	100.0

1/30/89

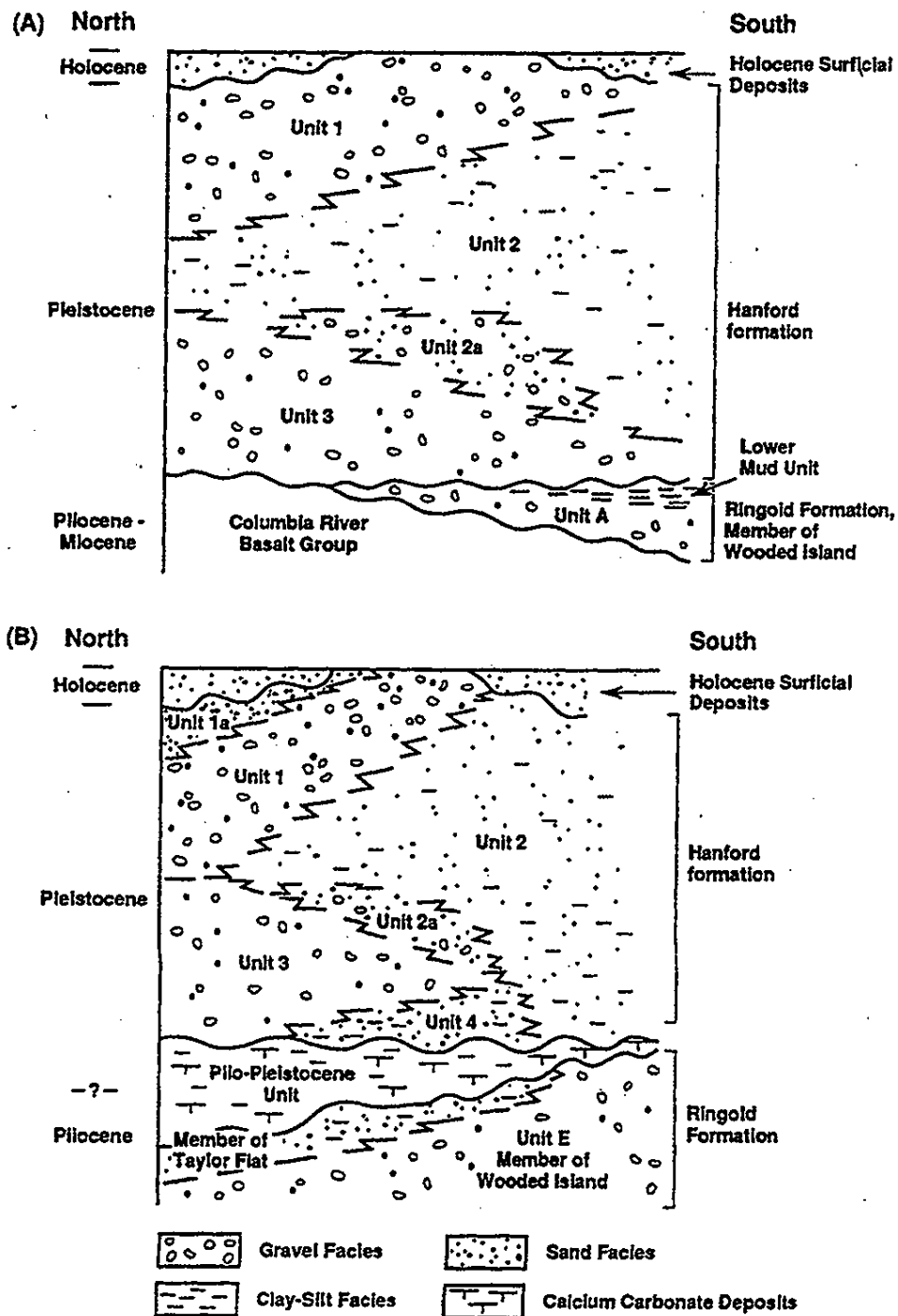
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**** REPORT ON WELL 0290-E33-084 ****

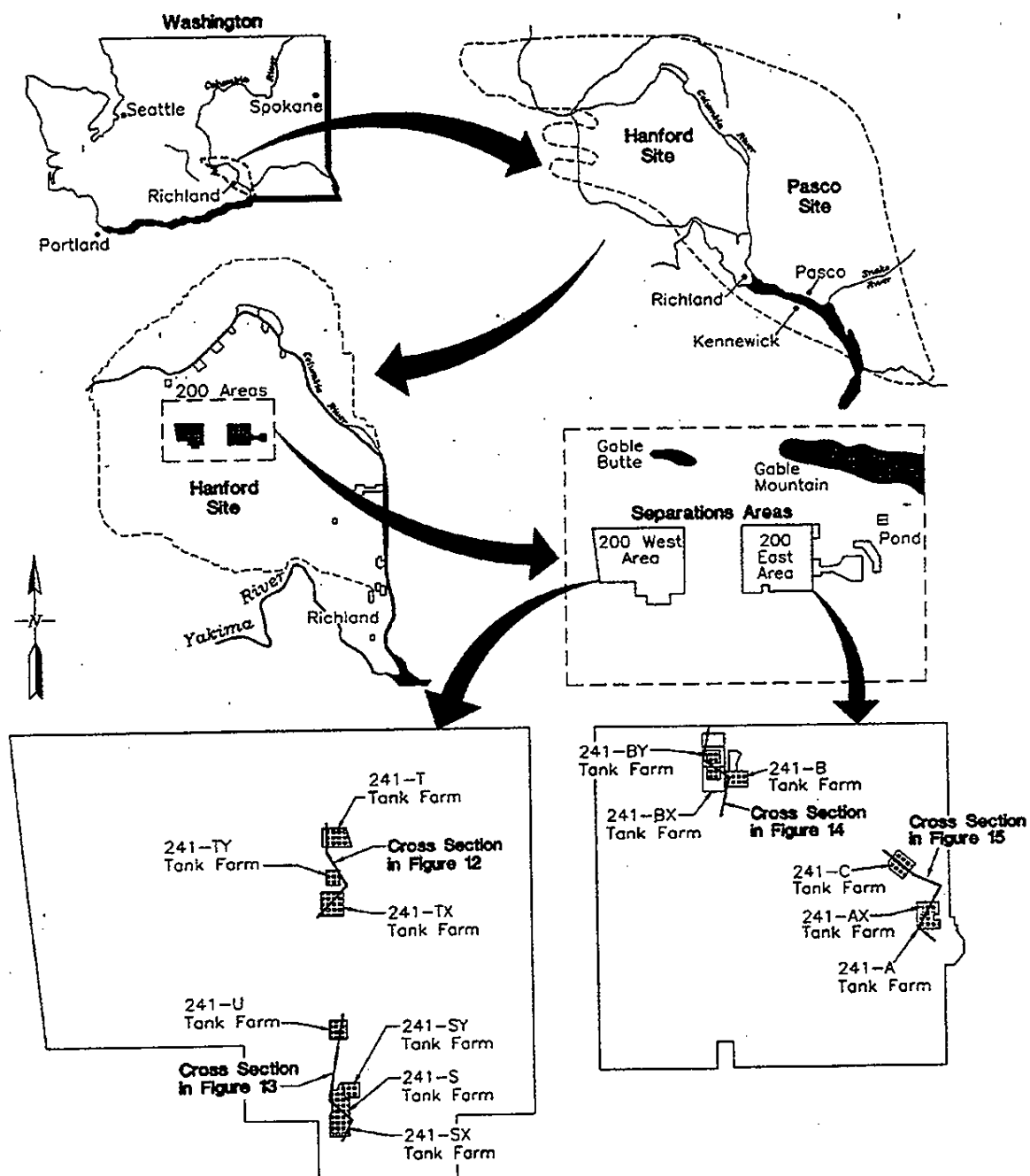
DEPTH	XCARC03	DM	XSD	XSRND	XGRAVEL	CLASS	FINE PES (-2)	VFINE PES (-1)	VERY COARS (0)	COARS (1)	MED (2)	FINE (3)	VERY FINE (4)	SILT (4.75)	PAH (4.75)
100	1.0 C	12.0	84.4	3.6	(m)S		1.1	4.6	18.3	48.4	38.8	18.6	8.8	6.3	12.6
SORT=	1.63	MEDIAN=	2.00	MODE=	1.00	PERN=	0.7	2.9	11.6	30.7	24.6	11.8	5.7	4.0	8.0
SPLIT	160.0						CUM	0.7	3.6	15.2	45.9	70.5	82.4	90.0	100.0
105	1.1 C	13.6	83.3	3.1	(m)S		0.4	4.4	19.1	53.9	33.7	14.3	8.7	6.5	14.7
SORT=	1.77	MEDIAN=	2.00	MODE=	1.00	PERN=	0.3	2.8	12.3	34.6	21.6	9.2	5.6	4.2	9.4
SPLIT	156.4						CUM	0.3	3.1	15.4	50.0	71.8	80.8	86.4	100.0
110	1.8 C	9.3	88.3	2.3	S		0.0	3.9	45.9	58.8	27.5	9.7	5.8	4.9	10.7
SORT=	1.48	MEDIAN=	1.00	MODE=	1.00	PERN=	0.0	2.3	27.4	35.2	16.4	5.8	3.5	2.9	6.4
SPLIT	167.9						CUM	0.0	2.3	29.8	64.9	81.4	87.2	90.7	100.0
115	1.1 C	8.3	73.1	18.6	(m)S		1.3	26.8	42.8	36.1	19.1	9.2	5.1	4.1	8.4
SORT=	1.67	MEDIAN=	1.00	MODE=	0.00	PERN=	0.8	17.8	29.0	22.6	12.7	5.4	3.4	2.7	5.8
SPLIT	151.7						CUM	0.8	18.6	47.7	70.3	82.9	88.3	91.7	100.0
120	1.0 C	12.5	83.6	3.9	(m)S		0.3	5.9	19.7	43.5	43.9	17.6	8.7	6.2	13.8
SORT=	1.68	MEDIAN=	2.00	MODE=	2.00	PERN=	0.2	3.7	12.3	27.3	27.5	11.0	5.5	3.9	8.7
SPLIT	160.8						CUM	0.2	3.9	16.2	43.5	71.0	82.0	87.5	100.0
125	0.9 C	13.4	82.8	3.8	(m)S		0.3	8.1	31.3	58.9	29.8	14.4	8.8	6.8	15.8
SORT=	1.92	MEDIAN=	1.00	MODE=	1.00	PERN=	0.2	3.6	18.6	37.8	17.7	8.5	5.2	4.0	8.4
SPLIT	169.1						CUM	0.2	3.8	22.4	55.1	72.9	81.3	86.6	100.0
135	0.7 C	7.8	86.8	5.4	(g)S		0.1	8.2	38.6	54.9	28.9	9.7	5.1	3.9	8.2
SORT=	1.56	MEDIAN=	1.00	MODE=	1.00	PERN=	0.1	5.3	23.5	37.3	18.6	8.5	5.2	3.3	5.3
SPLIT	156.3						CUM	0.1	5.4	28.9	64.2	82.7	89.0	92.2	100.0
140	0.8 C	15.2	78.7	6.1	(g)S		0.8	9.1	33.8	41.2	26.6	13.8	9.4	7.2	16.9
SORT=	2.20	MEDIAN=	1.00	MODE=	1.00	PERN=	0.4	5.7	21.3	28.0	18.8	8.7	5.9	4.5	10.7
SPLIT	159.9						CUM	0.4	6.1	27.4	59.4	70.2	78.9	84.9	100.0
150	0.8 C	13.9	82.9	2.1	(m)S		0.0	3.0	19.4	43.3	33.4	14.0	8.0	6.1	13.5
SORT=	1.82	MEDIAN=	2.00	MODE=	1.00	PERN=	0.0	2.1	13.8	30.8	23.7	19.0	5.7	4.3	9.8
SPLIT	142.0						CUM	0.0	2.1	15.9	48.7	70.4	80.4	88.1	100.0

Figure A-10. Generalized Geology Beneath SST Farms in the 200 East (A) and West (B) Areas.



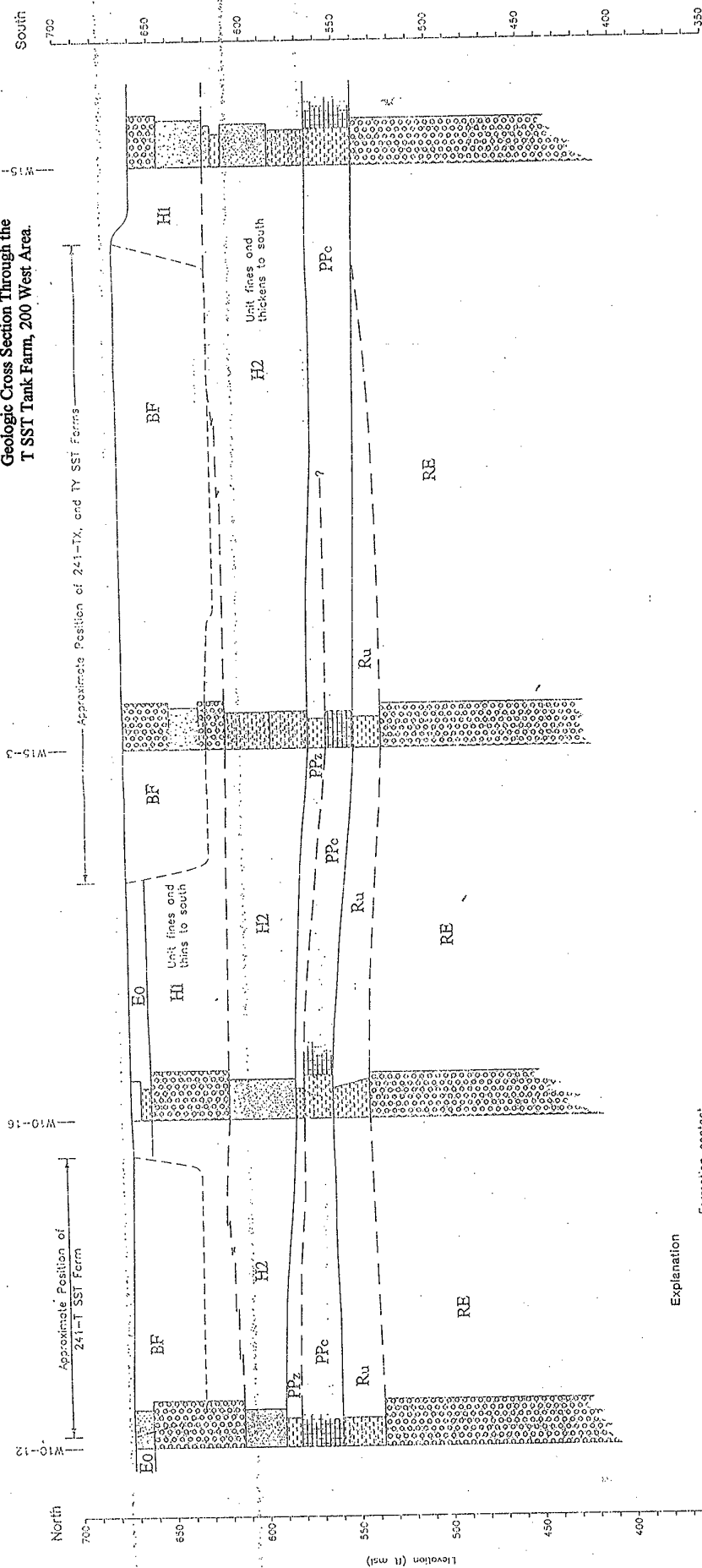
H96010075.8

Figure A-11. Location Map for the Geologic Cross Sections Shown in Figures 12 Through 15.



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Figure A-12. Generalized North-South
Geologic Cross Section Through the
T SST Tank Farm, 200 West Area.



Explanation	Formation contact	Unit/member contact	Unit/member contact
	--- Formation contact	--- Unit/member contact	--- Unit/member contact
	--- Base of backfill	--- Base of backfill	--- Base of backfill
	Gravel-rich strata ± sand ± silt	Gravel-rich strata ± sand ± silt	Gravel-rich strata ± sand ± silt
	Sand-rich strata, with minor gravel	Sand-rich strata, with minor gravel	Sand-rich strata, with minor gravel
	Sand-rich strata	Sand-rich strata	Sand-rich strata
	Sand-rich strata, with minor silt	Sand-rich strata, with minor silt	Sand-rich strata, with minor silt
	Silt-rich strata	Silt-rich strata	Silt-rich strata
	Calcium carbonate rich strata	Calcium carbonate rich strata	Calcium carbonate rich strata

Vertical Exaggeration: 4X

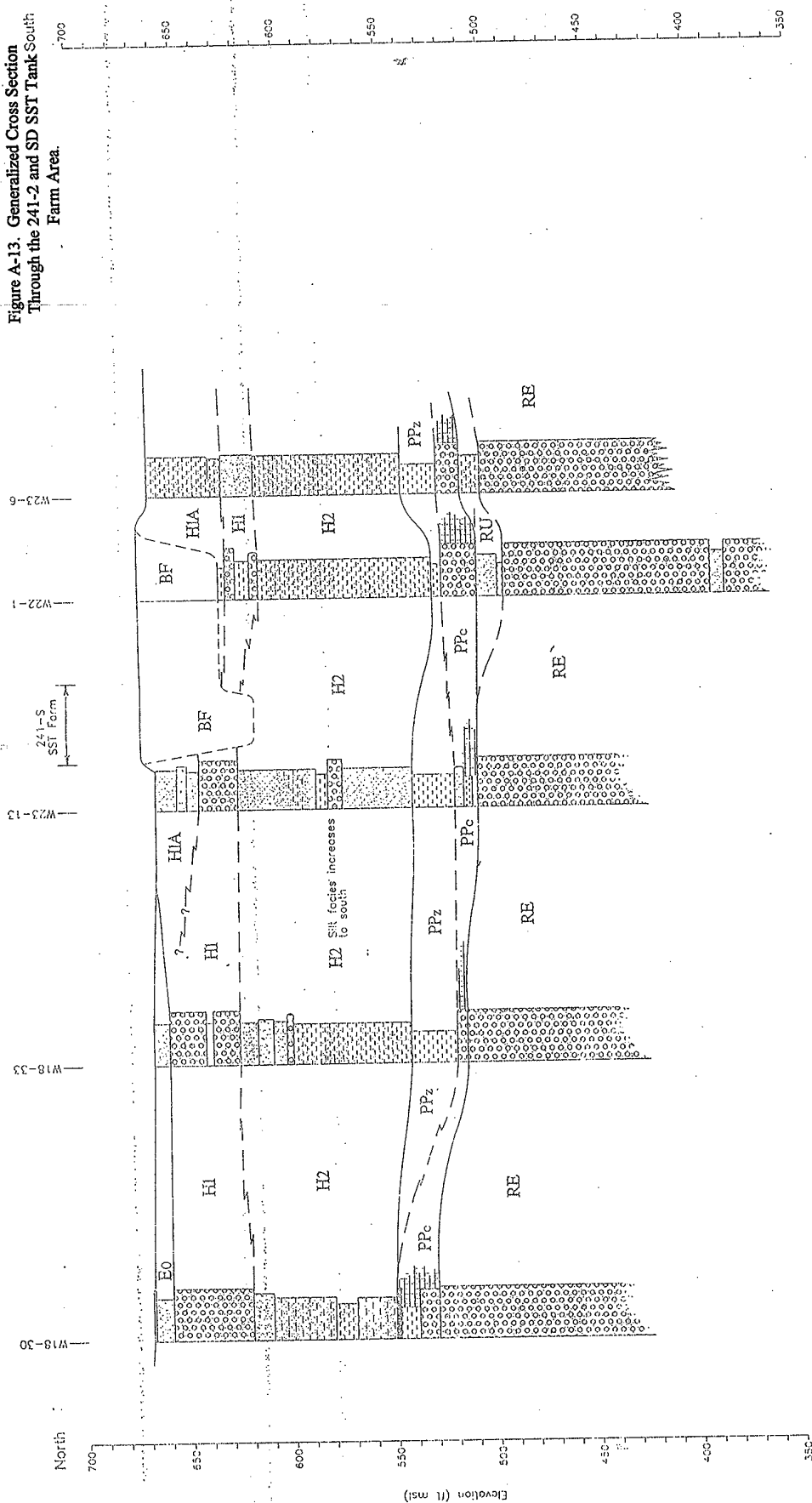
HANFORD TANK FARM
Generalized North-South Geologic
Cross Section Through the T SST
Tank Farm, 200 West Area

Figure 12

A-39/A-40

















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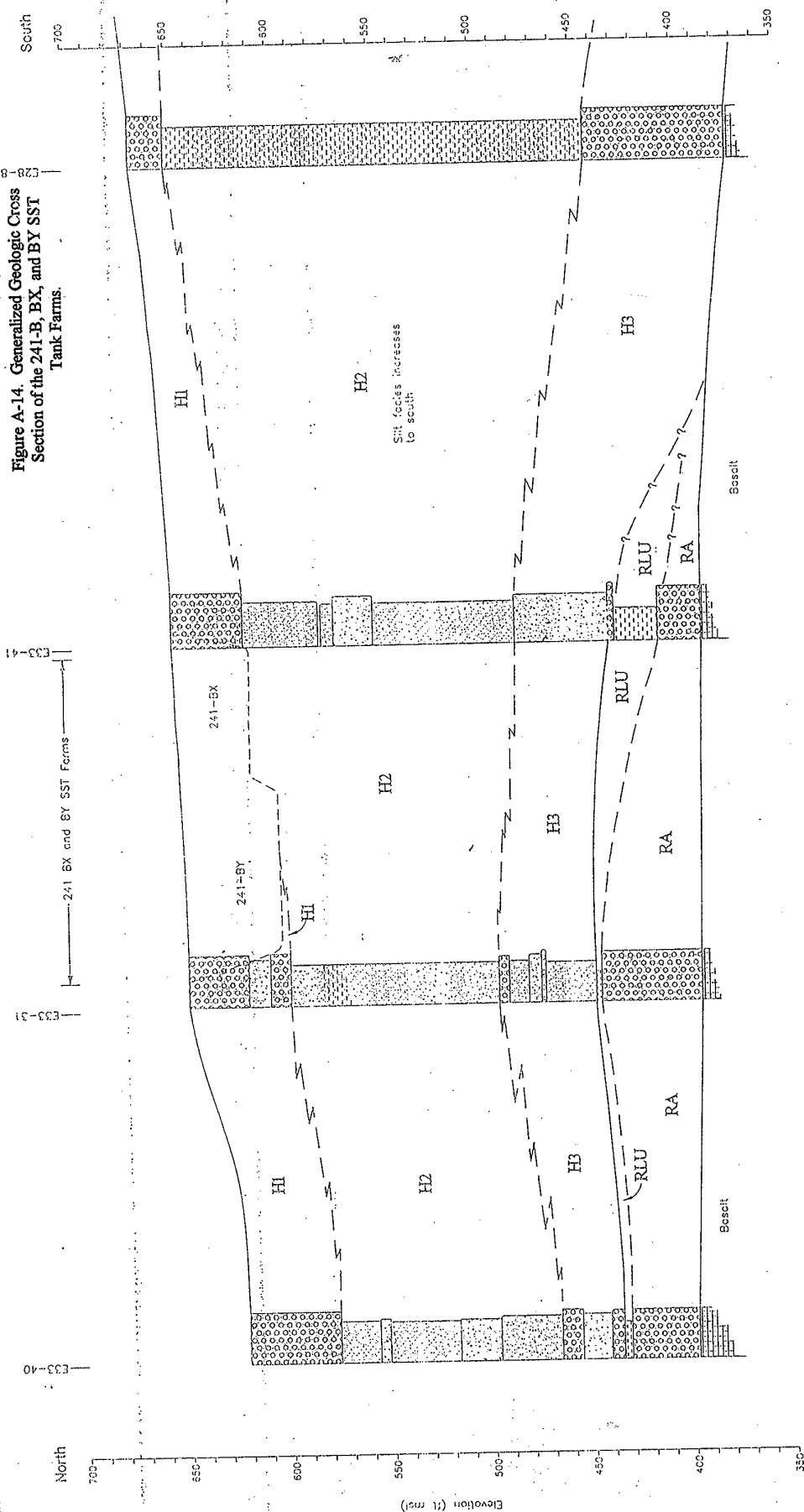
9

Vertical Exaggeration: 10X

Formation	Unit	Member	Contact	Base of	Base Unit
 Gravel-rich strata, ± sand & silt	 Sand-rich strata, with minor gravel	 Silt-rich strata	 Calcium carbonate rich strata	Eo	Holocene eolian material
				PPz	Flo-Pleistocene silt
 Sand-rich strata, with minor gravel	 Silt-rich strata	 Silt-rich strata	 Calcium carbonate rich strata	BF	Beckfill
				PPc	Flo-Pleistocene carbonate and alluvium
 Sand-rich strata	 Silt-rich strata	 Silt-rich strata	 Calcium carbonate rich strata	Hi	Harford Formation, Unit 1
				Ru	Ringold Formation, member of Taylor Flat
 Sand-rich strata	 Silt-rich strata	 Silt-rich strata	 Calcium carbonate rich strata	H7	Harford Formation, Unit 2
				RE	Ringold Formation, member of Roesse Island, Unit E

HANFORD TANK FARM
Generalized Geologic
Cross-Section Through
the 241-S and SX
SST Tank Farm Area







Figure A-14. Generalized Geologic Cross Section of the 241-B, BX, and BY SST Tank Farms.



**HANFORD TANK FARM
Generalized Geologic
Cross-Section in
the Area of the 241-B,
BX, and BY SST Farms**

PPz	Plio-Pleistocene silt
PPc	Plio-Pleistocene carbonate and alluvium
Ru	Ringold formation, member of Taylor flat
RE	Ringold formation, member of Wooded island, Unit E

E0	Helocene ecion material
BF	Sackville
HI	Harford Formation, Unit 1
H2	Harford Formation, Unit 2

	Gravel-rich strata with minor silt		Sand-rich strata with minor silt
	Sand-rich strata;		Silt-rich strata
	Sand-rich strata		Calcium carbonate rich strata

Explanation	Formation contact	Unit/member contact	Base of
-------------	-------------------	---------------------	---------

200 ft

Vertical Exaggeration 4X

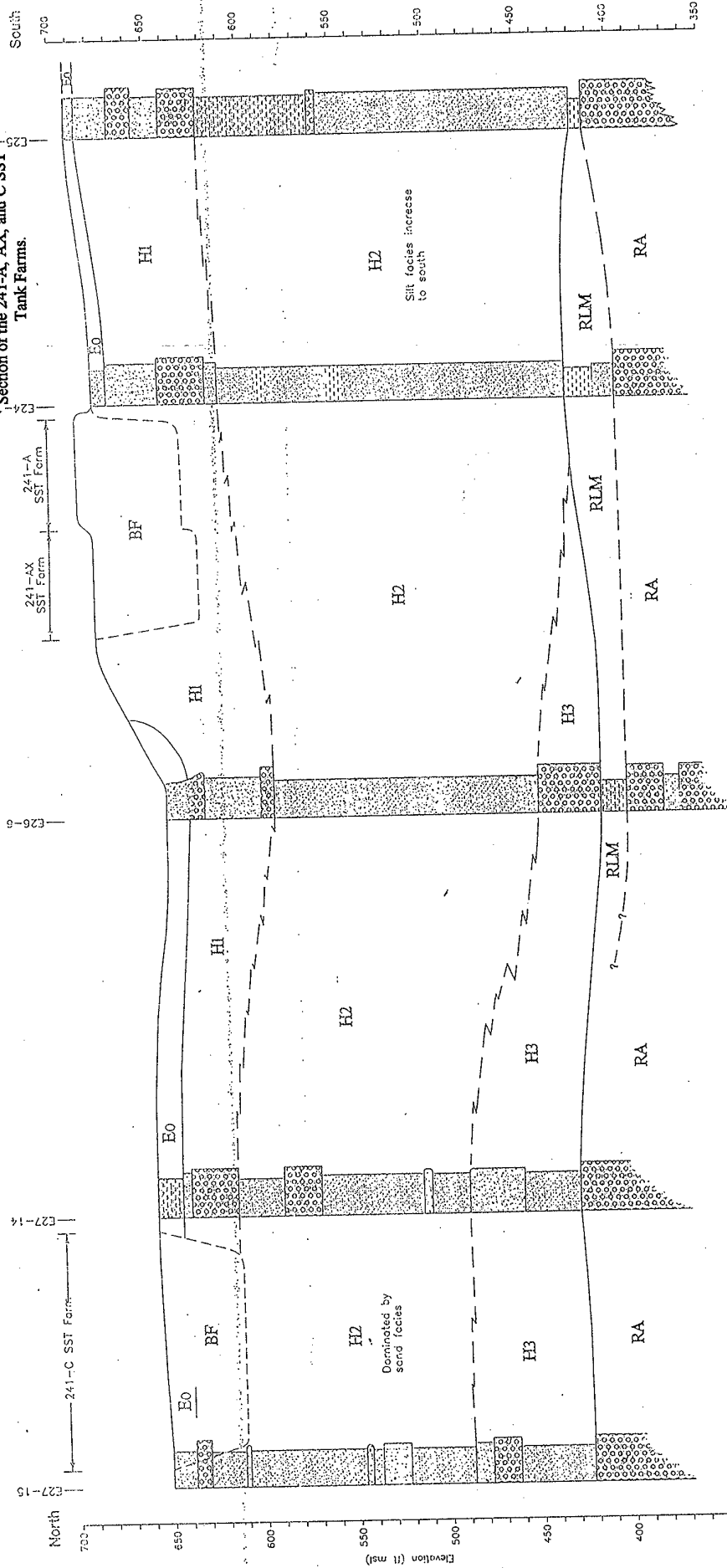
Figure 14

A-43/A-44

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Figure A-15. Generalized Geologic Cross-Section of the 241-A, AX, and C SST Tank Farms.



Explanation

- Formation contact
- - - Unit/member contact
- - - Base of backfill
- Gravel-rich strata ± sand ± silt
- Sand-rich strata with minor gravel
- Sand-rich strata
- Sand-rich strata with minor silt
- Silt-rich strata
- Calcium carbonate rich strata
- Holocene erosion material
- Bockfill
- Hanford Formation, Unit 1
- Hanford Formation, Unit 2
- Plio-Pleistocene silt
- Plio-Pleistocene carbonate and alluvium
- Ringold Formation, member of Taylor Fict
- Ringold Formation, member of Wooded Island, Unit E

Vertical Exaggeration: 4x

50 ft

200 ft

HANFORD TANK FARM
Generalized Geologic Cross-Section
in the Area of the 241-A,
AX and C SST Farms

Figure 15

A-45/A-46

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APPENDIX B
TANK FARM HYDROLOGY

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APPENDIX B

TANK FARM HYDROLOGY

B1.0 INTRODUCTION

Tank leaks occur under variably saturated conditions; natural recharge from meteoric water and vadose zone hydrology are therefore important drivers for contaminant movement to groundwater. This document provides detailed discussions on recharge, vadose zone, and groundwater conditions at tank farms.

Recharge or deep percolation is the process by which the surplus of infiltration over evapotranspiration drains below the plant root zone and moves downward through the vadose zone toward the water table. Recharge rates must be known to assess the potential for groundwater contamination beneath tank farms. No direct measurements of recharge are available for tank farms. Instead, recharge estimates for tank farms are based on studies elsewhere on the Hanford Site as reported by Fayer et al. (1996), Fayer and Walters (1995), Gee et al. (1993) and Gee et al. (1992).

B2.0 RECHARGE ESTIMATES AT THE HANFORD SITE

Studies conducted over the last 25 years at the Hanford Site indicate that recharge can vary greatly depending on factors such as climate, vegetation, surface condition, and soil texture. While recharge can be estimated by a variety of indirect methods, primarily revolving around water budgets, these techniques often are inappropriate for arid environments because of the very small fluxes involved (Gee and Hillel 1988). Therefore, most recharge data at the Hanford Site have been measured directly using a combination of drainage and weighing lysimeters (Rockhold et al. 1995; Gee et al. 1992). A variety of soils, surface conditions, vegetation, and climatic conditions have been studied (Table B-1).

Clearly, recharge is directly related to annual precipitation; where recharge is observed, more precipitation implies more recharge. Also, recharge has been shown to depend on the seasonal distribution of precipitation, with maximum recharge events occurring following the wettest winters. Under normal conditions, the recharge rate is highest in coarse-textured soils without vegetation and is at the measurement threshold in fine-textured soils with or without vegetation. Coarse soil surfaces that are either vegetated with shallow-rooted species or are bare exhibit recharge on the order of 50 percent of precipitation. Routson and Johnson (1990) reviewed water infiltration data from a 13-year observation period for a closed-bottom lysimeter located in the 200 East Area and ¹³⁷Cs profile data from a solid-waste burial ground trench in the 200 West Area. The recharge rate of the closed-bottom lysimeter was estimated to be 0.0 to 0.2 cm/yr over the 13 years.

Limited data based on the application of environmental tracer techniques generally are consistent with data from the lysimeters. The tracer data indicate that undisturbed vegetated sites have experienced as little as 0.001 to 0.01 cm/yr of recharge and as much as 0.3 to 0.4 cm/yr (Prych 1995). However, the tracer techniques, while powerful, do not apply at disturbed sites such as tank farms, and have been unable to measure significant rates of recharge at sites with coarse soils and shallow-rooted vegetation because of deep percolation of the natural tracers at these sites.

In addition to studies using lysimeter and tracer techniques, a number of studies have been conducted to estimate recharge regionally. For example, Bauer and Vaccaro (1990) estimated groundwater recharge for the Hanford Site as part of their study of recharge affecting the Columbia Plateau regional aquifer. Using estimates of soil type and land use and a water balance model, they estimated recharge rates for most of the Site ranging from 0 to 1.27 cm/yr. In contrast, near the sand dunes in the middle of the Site, they estimated rates as high as 5.1 cm/yr.

B3.0 RECHARGE ESTIMATES AT TANK FARMS

The tank domes are covered with about 2 m of backfill. The backfill material, taken largely from the Hanford formation, primarily consists of gravels mixed with a finer fraction. Some of the tank surfaces, however, are covered by a layer of clean gravel with median particle size distribution on the order of tens of millimeters (Smoot et al. 1990). The coarse backfill sediments, kept free of vegetation, can allow a significant portion of the annual precipitation to infiltrate and drain into the vadose zone sediments.

As stated earlier, recharge measurements for gravel-covered tank dome surfaces are not available. However, drainage data from gravel-covered lysimeters located at the Field Lysimeter Test Facility (FLTF) (Gee et al. 1993) can be used to mimic conditions at tank farms. Fayer et al. (1996) and Fayer and Walters (1995) estimated recharge rates based on numerical modeling and measurements of drainage, water content, and tracers. Estimates were assigned to specific soil-vegetation combinations and distributed across the Hanford Site using a soil map and a vegetation/land use map. The long-term average rates varied from 0.26 cm/yr for several soil and vegetation combinations in the 200 Areas to 12.7 cm/yr for basalt outcrop with no vegetation at the crest of the Rattlesnake Mountain (Fayer and Walters 1995). To estimate recharge for gravel-covered sites in the 200 Areas, Fayer and Walters (1995) and Fayer et al. (1996) used the measured drainage rate beneath the 15 cm gravel-covered lysimeters at the FLTF as a surrogate (Gee et al. 1993). Under 3 years of ambient precipitation (184 mm/yr), this rate was 86.7 cm/yr, or about 47 percent of precipitation. For a long-term precipitation of 160 mm/yr, this translates to a recharge rate of about 75 mm/yr. Under 3 times normal precipitation (480 mm/yr), the recharge rate for the gravel-covered lysimeters at the FLTF was 300 mm/yr, or about 62.5 percent of precipitation. At a precipitation rate of 240 mm/yr (1.5 times the normal precipitation), Fayer and Walters (1995) reported the associated drainage beneath a gravel-covered soil as being 127.1 mm/yr, or about 53 percent of precipitation. Note that drainage data based on a 15 cm-thick gravel layer are being extrapolated to a 75-ft-diameter tank covered with a 2 m-thick layer of gravel. Also, the FLTF site contains clean gravels, whereas the tank farms are covered with gravels mixed with finer fraction, which allows for less drainage.

An enhanced recharge, known as the umbrella effect, can be caused by water shedding from the impermeable tank domes around the circumference of the tank (Ward et al. 1997, Kline and Khaleel 1995). Using numerical simulations, Ward et al. (1997) showed that moisture contents can reach 0.25 (on a volume basis) around tank perimeters. This high value can be attributed to the enhanced recharge. With a 22.86 m (75-ft) tank diameter, a recharge rate of 75 mm/yr for a long-term precipitation of 160 mm/yr translates to a recharge around the perimeter of a gravel-covered tank of about 31 m³/yr, or 8,150 gal/yr. This volume is comparable to that of the majority of known leaks that occurred at the tank farms.

Using numerical simulations, Smoot et al. (1990) evaluated potential methods for reducing surface drainage at tank farms. When a 0.15 m-thick layer of silt loam soil cover was added to the tank farm surface, the drainage was reduced to less than 1 percent of the annual precipitation after 5 years (Smoot et al. 1990). In contrast, a surface of clean gravel increased the drainage to 95 percent of precipitation. When a relatively impermeable barrier was placed over the tank farm sediments, the drainage to a 2 m backfill depth decreased to less than 0.05 cm/yr after 8 years for cases of either a backfill or a clean graveled surface. These simulation results show that infiltration control can be improved dramatically using a layer of fine-grained soil cover.

During tank farm operations, some areas remained undisturbed; these can be considered representative of preoperations conditions. For the remaining areas, individual soil types are assumed to be altered by construction, excavation, and building roads and infrastructure. These soil types are treated as exposed sand. Vegetation is assumed to be minimal to nonexistent. For the exposed sands around tanks, 30.6 percent of precipitation can become recharge (Fayer and Walters 1995). For a long-term precipitation average of 160 mm/yr, this translates to a recharge rate of 49 mm/yr.

Note that the preceding recharge estimates assume isothermal conditions. In fact, some of the tanks are significant heat sources that potentially can induce sharp temperature gradients to the surrounding soil column. Thermal buoyancy, as well as vaporization and condensation, would likely contribute to redistribution of enhanced recharge around the tank.

B4.0 VADOSE ZONE HYDROLOGY AT TANK FARMS

Because water movement is the primary mechanism for radionuclide transport, our objective is to evaluate the potential for radionuclide transport beneath the tank farms by considering the nature and distribution of flow within the vadose zone.

B4.1 NATURE OF VADOSE ZONE FLOW

The nature of vadose zone flow is discussed in the context of two conditions; natural recharge and artificial recharge. In general, two types of moisture movement can occur in vadose zones; piston flow and preferential flow. Piston flow refers to uniform moisture movement through the soil matrix whereby infiltrated water displaces initial water. Under piston-like flow conditions most, if not all, preexisting ("old") water is displaced and moved ahead of the "new"

infiltration water added from above. Under natural recharge conditions, the medium to coarse-grained sands at tank farm sites are expected to be quite conducive to piston flow.

Preferential flow refers to nonuniform moisture movement along preferred pathways. During preferential flow, local wetting fronts may propagate to considerable depths in a soil profile, essentially bypassing the matrix pore space. While preferential flow has been recognized and widely studied under saturated or near-saturated flow conditions (e.g., Nkedi-Kizza et al. 1983; De Smedt and Wierenga 1984), arid and semiarid climates or areas under low-water fluxes, particularly where soils are coarse grained, such as under the tank farms, show little evidence of it. Thus, under natural recharge conditions, precipitation at arid sites usually is too low to invoke preferential flow; much of the water in the dry soils is simply adsorbed onto the grain surfaces and cannot move along preferred pathways. For tank leak conditions, Caggiano et al. (1996) presented several hypothetical sources and migration pathways for contaminant movement within the vadose zone (Figure B-1).

Clastic Dikes. Although, clastic dikes can potentially increase flow rate, they are unlikely to intersect large segments of leaked waste and, when they do, the cross sectional area of the intersection is small (DOE 1997). Therefore, the presence of clastic dikes in unsaturated media appears unlikely to contribute much to transporting the bulk quantity of leaked tank waste to groundwater. This said, the chances of a tank encountering a clastic dike are high, and contaminants could move along this preferential pathway. Many clastic dikes are present at the U.S. Ecology site southwest of the 200 East Area.

Fingering and Funneled Flow. Other potential preferential pathways during tank leaks include "fingering" flow and "funneled" flow (DOE 1997). Fingering flow results when media instabilities cause uniform flows to split into fingers. Funneled flow results when media heterogeneities cause the flow area to shrink (Kung 1990).

A simulated tank leak study in the 200 East Area (Narbutovskih et al. 1996) provided some evidence of preferential flow; electrical resistivity tomography data indicate that relatively small volumes (<50,000 L) of liquid waste can reach depths of >30 m within the vadose zone in tens of days. Also, spectral gamma logging of drywells surrounding the tanks of the 241-SX farm determined that ^{137}Cs is present at depths of 20 to 25 m beneath the tank farms (GJPO 1996). Each potential preferential flow method has a different cross sectional area available for intersecting tank leaks. According to DOE (1997), colloid-assisted preferential flow provides the greatest probability of intersection, because the entire formation area below the leaked waste becomes available for migration.

B4.2 VADOSE ZONE FLOW AND TRANSPORT IN HETEROGENEOUS MEDIA

A basic parameter for evaluating flow in an unsaturated zone is water content. Under natural recharge conditions, the water content profiles are at quasi-equilibrium with the recharge rate. A 1980 field study (Sisson and Lu 1984) in the 200 East Area south of the Plutonium-Uranium Extraction (PUREX) Plant demonstrated the effect of geologic heterogeneities on water

contents in a natural arid setting; the higher observed water content values were strongly correlated with fine soil layers. In addition, the observed water content profiles were remarkably similar for the 15-year interval between measurements at the Sisson and Lu field site (Fayer et al. 1995). This shows that, in the absence of artificial recharge, the "natural" moisture contents of the sediments are essentially determined by the nature of geologic heterogeneities. This is supported by the moisture content profiles in borehole 299-W10-196 near tank 241-T-106 in the 200 West Area; the data collected in 1993 show a much higher moisture content in the Plio-Pleistocene unit and upper Ringold Formation than in the Hanford formation (Freeman-Pollard et al. 1994).

No direct measurements of water contents are available during or following tank leaks. However, to mimic unsaturated flow and transport conditions during injection, a test facility consisting of an injection well at the center of a radial array of 32 monitoring wells was constructed in the 200 East Area. About 45,000 L (12,000 gal.) of liquid were injected at a depth of 4.7 m in 11 injections over 133 days (Sisson and Lu 1984). Three-dimensional water content profiles in layered, coarse sediments were monitored to a depth of 18 m using down-hole neutron probe measurements. Because of the unique three-dimensional nature of the experiment, measurement of water content and radioactive tracers in situ, and the use of multiple injections, the results of this study provide an important database to study potential conditions within the vadose zone during tank leaks. In addition to verifying the importance of layering, the field data clearly show lateral spreading that occurred during injection. The horizontal wetting patterns, which dominated the experiment, were not anticipated, given the rather uniform Hanford formation lithology at the site. However, the dominance of lateral flow is a unique feature of unsaturated flow, especially in an arid setting. Such a field-scale process is referred to as tension-dependent anisotropy (Yeh et al. 1985). Lateral movement is caused by the relatively high tensions occurring in dry sediments. Horizontal stratification enhances such movements because, at high tension, hydraulic conductivities of fine-textured materials are relatively high and the fluid prefers to spread laterally in the fine media than to move vertically through the coarse media.

Routson et al. (1979) investigated the 435,321 L (115,000-gal.) leak that occurred in 1973 from tank 241-T-106 in the 200 West Area. The soil is part of the Hanford formation consisting primarily of pebbly and medium sand. Measurements of vadose zone contamination in wells around the T-106 tank indicated significant lateral movement of waste in the sediment layers, at least in the initial stages of the leak, between 1973 and 1974. At later stages of the leak, flow was so slow that lateral movement could not be detected because the radioactive decay of the tracers is relatively rapid (^{106}Ru has a half-life of approximately 1 year). During 1973 and 1974, lateral spread was much larger than the diameter of the tank, while vertical movement was restricted to a few tens of meters. During a 1993 investigation, contaminants from the 1973 leak were found to be still confined within the vadose zone at about 21 m above the water table. The ^{99}Tc appears to be centered in the fine-grained strata of the upper Ringold Formation and the Plio-Pleistocene and early Palouse units; and its concentrations decline sharply at the contact with Ringold unit E. Both mobile and attenuated radionuclides were concentrated in Plio-Pleistocene caliche horizons near 30 m (98 ft) depth (Freeman-Pollard et al. 1994).

In summary, at a macroscopic scale in unsaturated, thinly layered heterogeneous media, such as those existing under tank farms, textural heterogeneities result in a variable anisotropy that increases with an increase in tension (i.e., a decrease in moisture content). Therefore, as the soil gets drier, the anisotropy is enhanced, resulting in lateral flow being dominant over vertical flow. For tank leaks, this has important implications on contaminant arrivals at the water table.

B5.0 EXISTING SOIL HYDRAULIC PROPERTIES IN THE 200 AREAS

Geologic heterogeneities and soil hydraulic properties (i.e., the relationships between moisture content and matric potential and unsaturated hydraulic conductivity and moisture content) must be known to evaluate the storage and flow properties of tank farm soils. Furthermore, assessing the ability of the vadose zone to act as a buffer requires properly accounting for conditions whereby the tank leak chemistry itself may affect soil hydraulic properties and therefore the mobility of contaminants. Very little site-specific data are available on soil hydraulic properties under normal conditions for individual tank farms. Of course, no data are presently available that explain to what extent, if any, past leaks have altered the hydraulic properties of sediments underneath the tank farms. Nonetheless, over the years, data have been obtained on soil properties in the 200 Areas. Much of these data have been gathered as part of Site characterization activities for the Environmental Restoration Program. This section summarizes the existing data.

Khaleel and Freeman (1995) compiled available data for the principal formations and soil types in the 200 Areas plateau. Information on particle-size distribution, moisture retention, and saturated hydraulic conductivity (K_s) is available for 183 samples from 12 sites in the 200 Areas (Table B-2). Data on moisture retention and K_s were corrected for gravel content (Khaleel and Relyea 1997). After the data were corrected and cataloged, hydraulic parameters were determined by fitting the van Genuchten (1980) soil-moisture retention model to the data. A nonlinear parameter estimation code, RETC (van Genuchten et al. 1991), was used. The unsaturated hydraulic conductivity relationship was estimated using the van Genuchten parameters, Mualem's (1976) model, and laboratory-measured saturated hydraulic conductivity estimates. Alternatively, provided unsaturated conductivity measurements are available, the moisture retention curve-fitting parameters, Mualem's model, and a single unsaturated conductivity measurement can be used to predict unsaturated conductivities for the desired range-of-field-moisture regime (Khaleel et al. 1995).

The database, comprising 6 soil categories and 176 samples, was used as the basis for describing the probability distribution for the five hydraulic properties (i.e., van Genuchten curve-fitting parameters α and n ; residual volumetric moisture content θ_r , saturated volumetric moisture content θ_s , and K_s). Empirical cumulative distribution functions (CDF) were derived for all five parameters, and hypothesized distributions were fitted (Khaleel and Freeman 1995). Although the database was limited, the CDFs for all five parameters can be described using a normal distribution based on either the untransformed or the transformed variables (Table B-3).

A scaling technique for similar media with linearly variable hydraulic properties was applied to simplify the description of the spatial variability of 200 Area soils. Comparisons made

between the best fit van Genuchten curves for the unscaled data and those for the scaled data showed that scaling reduced the sums of squares by amounts varying from 63 to 89 percent (Khaleel and Freeman 1995). Results suggest that, for the soil types considered, scaling can be used successfully to describe the variability of soil hydraulic properties in the 200 Areas plateau.

In addition to parameter estimates, Table B-2 provides information on particle size distribution for samples that have been characterized in the laboratory for moisture retention. Because soil moisture retention properties are generally recognized to be related to soil texture (particle size distribution), available textural information (e.g., ROCSAN database for tank farm soils) can be matched to particle size distribution data found in Table B-2. Based on the appropriate match, selections can be made for van Genuchten parameters and K_s for tank farm soils.

Both unscaled and scaled data parameter statistics (Khaleel and Freeman 1995) can play an important role in characterizing the spatial variability of hydraulic properties at tank farm sites for a given soil horizon and between soil horizons. Therefore, updating the database as more data on soil properties become available is important. Also, data are needed on the alterations of hydraulic properties caused by leak chemistry.

B6.0 GROUNDWATER CONDITIONS BENEATH TANK FARMS

Groundwater flow and contaminant distribution in groundwater must be understood to discern the contribution of liquid discharges (via cribs, trenches, etc.) from tank leaks to concentrations in groundwater. This section summarizes current flow conditions and contaminant distributions in groundwater beneath the 200 Areas.

Before the Hanford Site was established in 1943, the unconfined aquifer flowed essentially from west to east. The introduction of large volumes of artificial recharge via pond, cribs, French drains, and injection wells has resulted in the development of groundwater mounds and increased gradients in the 200 Areas. Figure B-2 is a map of the Hanford Site and the adjacent area showing the water table during 1996. The most prominent features of the current water table map are the mounds located just east of the 200 East Area and in the western half of 200 West Area. These features correspond to the 216-B-3 Pond (B Pond) and U Pond, respectively. U Pond increases the hydraulic gradient from the west to east and reroutes flow in the north through the gap between Umtanum Ridge and Gable Mountain (Gable Gap). B Pond causes flow to reverse from east to west in portions of the 200 East Area; it also reroutes some flow to the north through the Gable Gap and some to the southeast of 200 East Area. Discharges to U Pond and B Pond have ceased and declines in mound height have been observed (Hartman and Dresel 1997). The mounds are expected to eventually dissipate and the flow conditions before Hanford Site operations will be restored. Note that the unconfined aquifer is underlain by the Columbia River Basalts; the basalts extend above the water table at some regions north of the 200 East Area.

In the 200 West Area, the water table lies in Ringold unit E gravels and is below the bottom of the Hanford formation. In most of the 200 East Area, the water table lies within the

Hanford formation. The Hanford formation in the 200 East Area is much more transmissive than the Ringold Formation in the 200 West Area; based on aquifer tests, saturated hydraulic conductivity of the Hanford formation ranges from 150 m/d to 1600 m/d, while that for the Ringold Formation ranges from 6 m/d to 180 m/d (Gephart et al. 1979). However, the groundwater flow in the 200 East Area is complicated by areas where Ringold unit E gravels, Ringold lower mud unit, and deeper Ringold Unit A gravels rise above the water table, forming lower permeability units in the saturated Hanford formation sediments (Hartman and Dresel 1997).

Contaminant plumes of concern in the 200 Areas include mobile, long-lived radionuclides such as ^{99}Tc , ^{129}I , ^3H , and uranium. Contaminant plumes are derived from discharge of low-level radioactive process waste to surface disposal facilities (ponds, cribs, French drains, and injection wells) and, potentially, tank leaks. Figures B-3 and B-4 show the Sitewide plumes for ^3H and ^{129}I , respectively. A large tritium plume has moved east from the 200 East Area and reached the Columbia River. Tritium from the 200 East Area also has migrated through Gable Gap to the north and reached the Columbia River. Tritium plumes at the 200 West Area are migrating north and east. However, these plumes are not as prolific as those from the 200 East Area because of the lower hydraulic conductivity and consequently, lower velocity of groundwater flow in 200 West Area. Johnson and Chou (1998) indicate that tritium is typically decanted from tank wastes and discharged to surface disposal facilities. Consequently, the source of tritium is most likely from cribs and ponds (Johnson and Chou 1998). Iodine plumes shown in Figure B-4 appear to originate from the same sources as the tritium plumes. The iodine shows the same degree of spread in each area that the tritium plume shows (i.e., broad in the 200 East Area and restricted in the 200 West Area).

Figure B-5 shows a ^{99}Tc plume originating in the 200 East Area and located in the vicinity of the B-BX-BY Tank Farms. The plume is elongated toward the north and extends through the Gable Gap. The most likely source of the plume could be the tanks, the nearby cribs, or a combination of both. Figures B-6 and B-7 show plumes of ^{99}Tc and uranium, respectively, in the 200 West Area. The large ^{99}Tc and uranium plumes originating from the area southwest of U Plant appear to be from the same source. Also, the ^{99}Tc plume is more elongated than the uranium plume. This reflects that ^{99}Tc is not retarded in its movement through the groundwater system, while the U plume is moderately retarded. The source of the release is speculated to be acid discharge to a crib (BHI 1996). The remaining ^{99}Tc and uranium plumes originate from separate sources (Figures B-6 and B-7).

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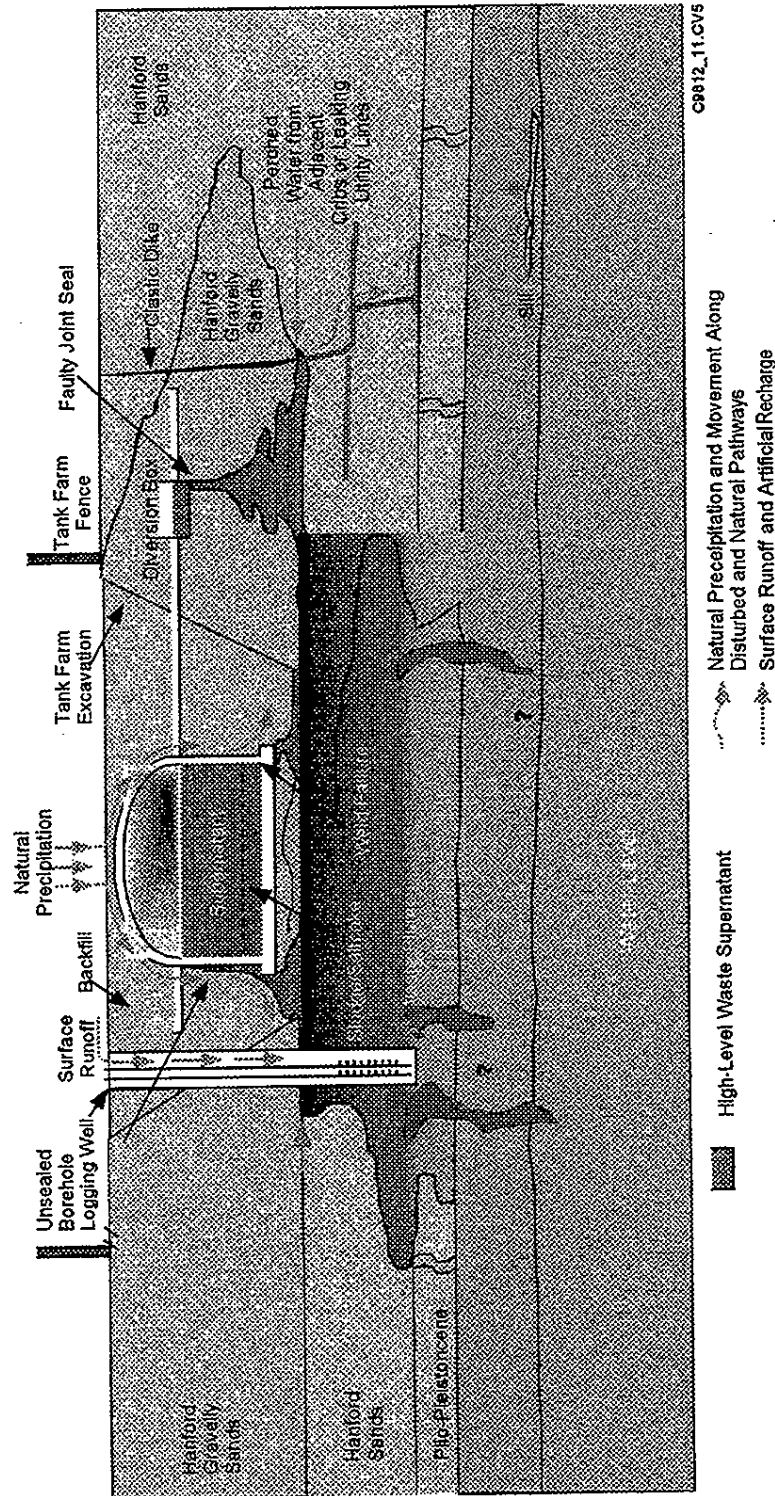
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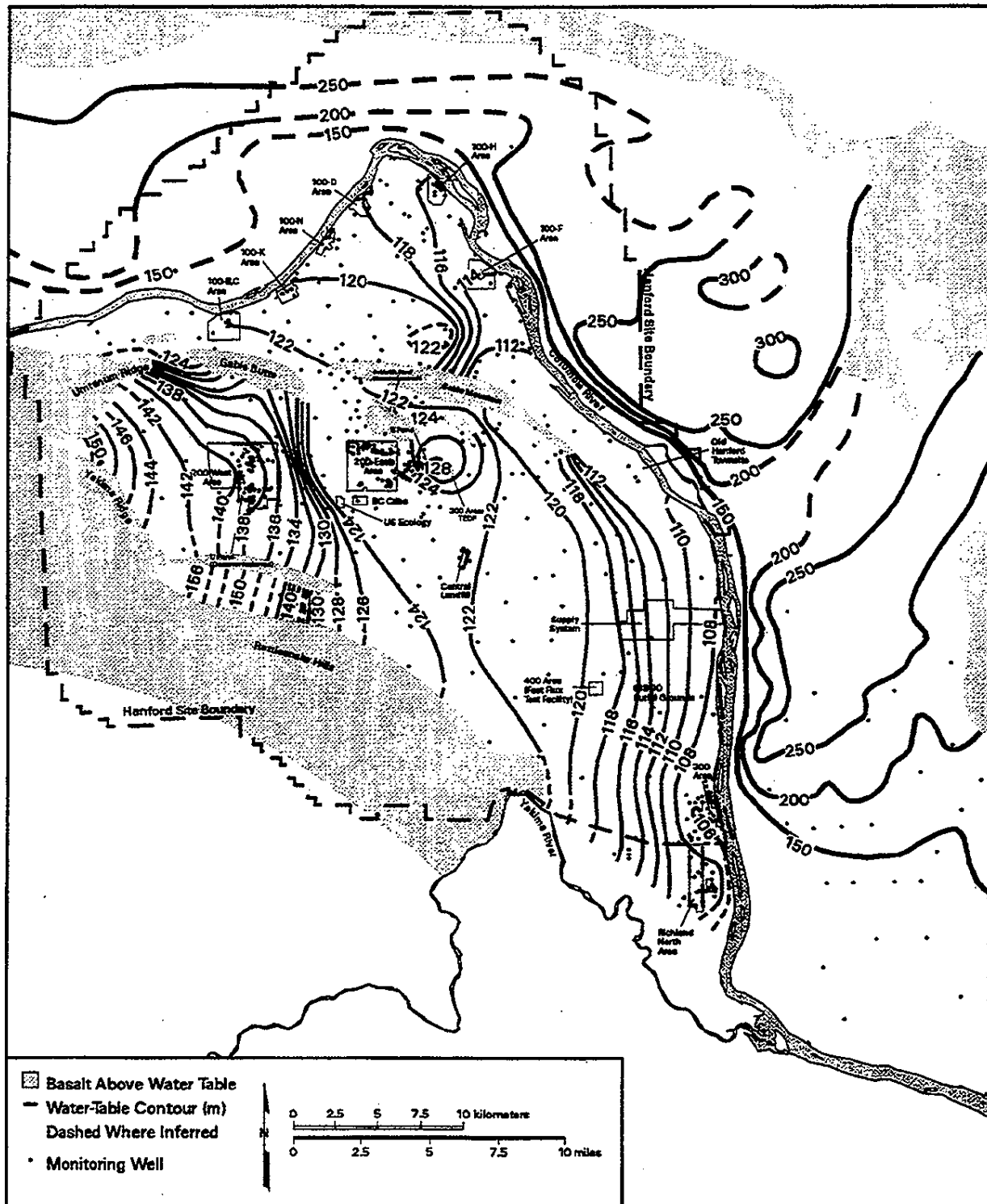
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Figure B-1. Soil Pathway Conceptual Model at the SX Tank Farm
(after Johnson and Chou 1998).



The tank waste and leakage shown are from early operations in the 1960s. Subsequent hypothetical movement of contaminants through the vadose zone covers a period from early operations to the present. As a result of volume reduction measures, a much smaller volume of free liquid remains in the tank today. Depth to groundwater is 64 m (201 ft). The tank base elevation is about 15 m (50 ft) below ground surface. The geologic strata shown are simplified for illustration purposes.

Figure B-2. Hanford Site and Outlying Areas Water-Table Map, June 1996.



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Figure B-3. Average Fiscal Year 1996 Tritium Concentration Contours.

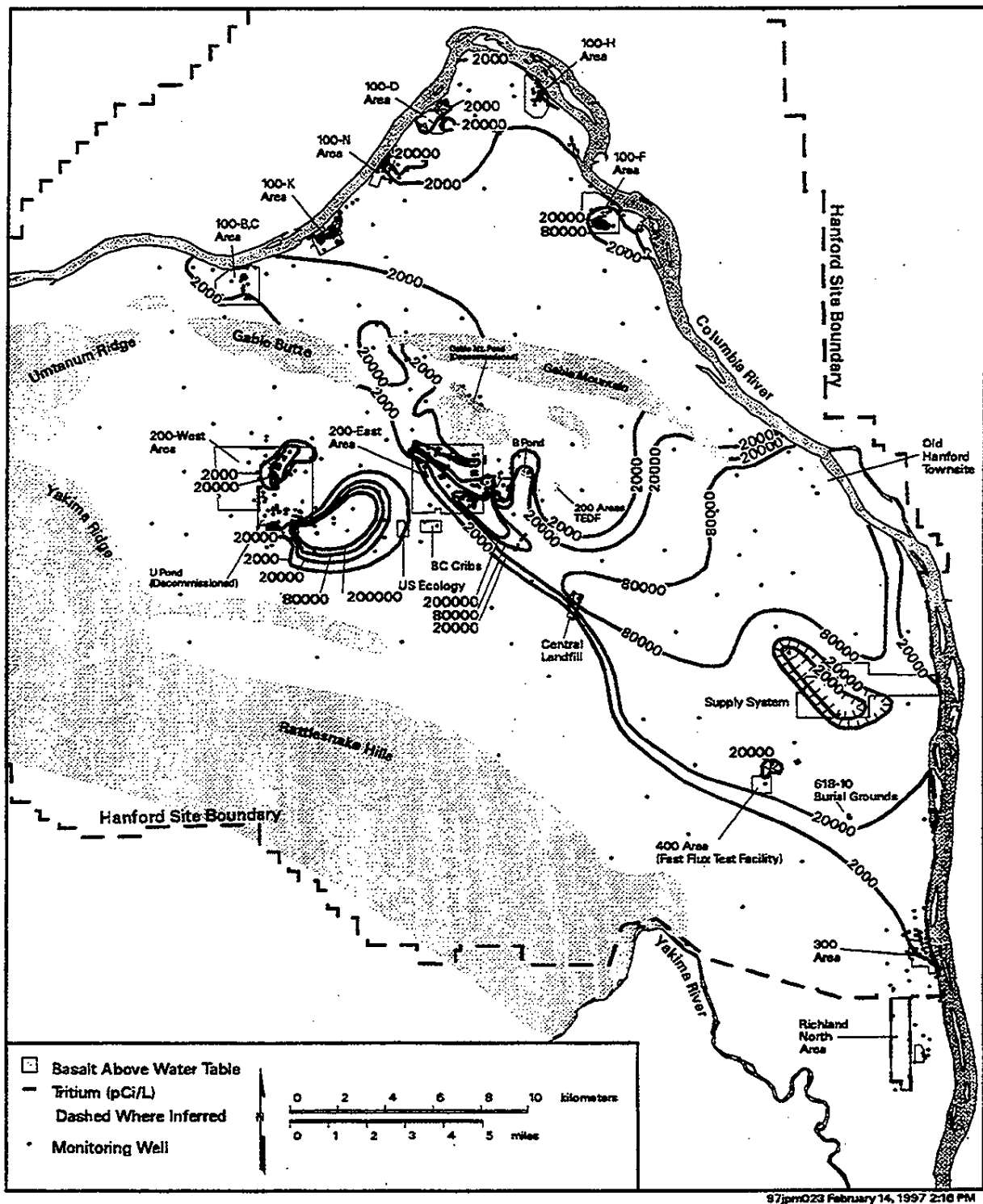
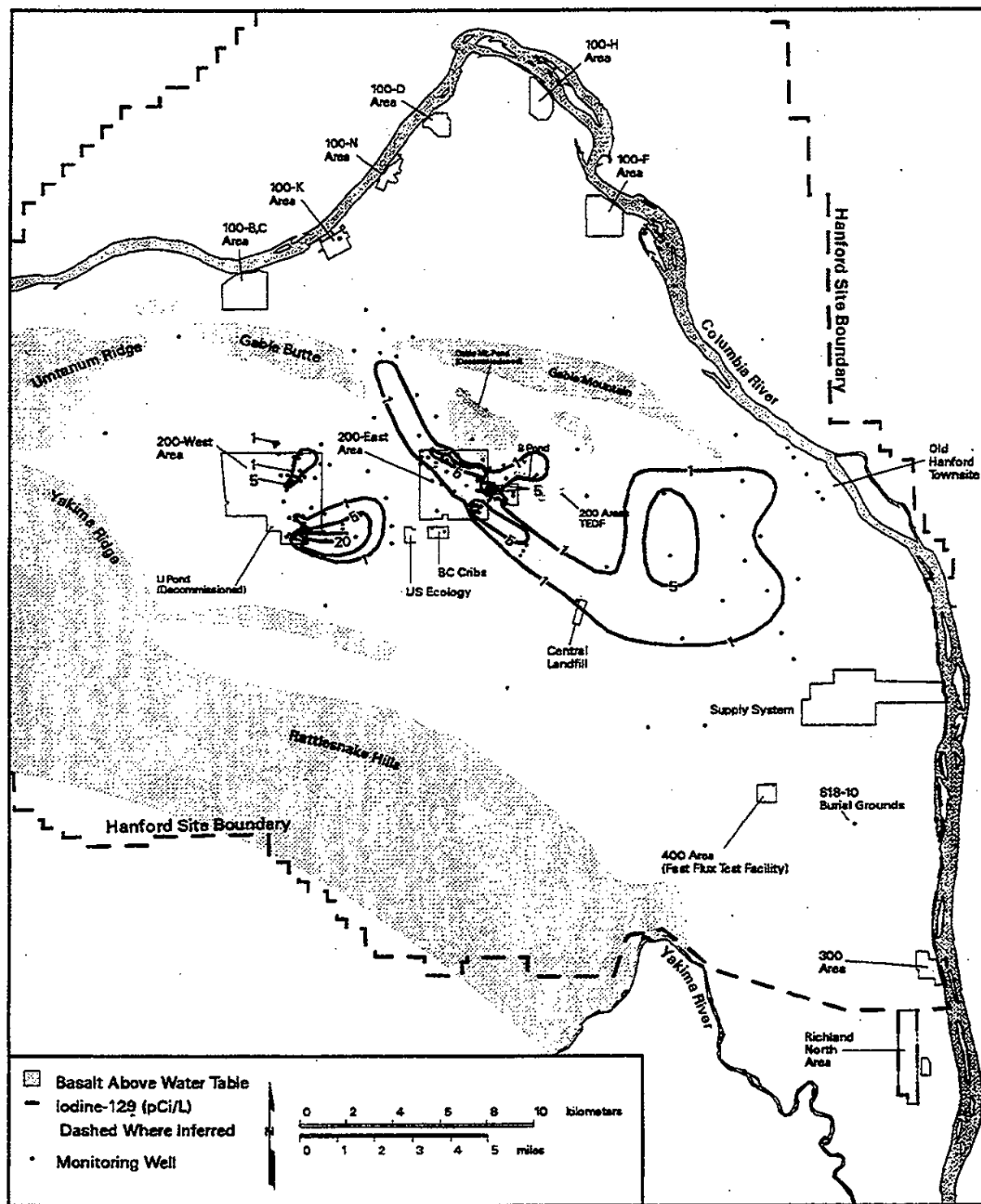


Figure B-4. Average Fiscal Year 1996 ^{129}I Concentration Contours.



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Figure B-5. Average Fiscal Year 1996 ^{99}Tc Concentrations in 200 East Area.

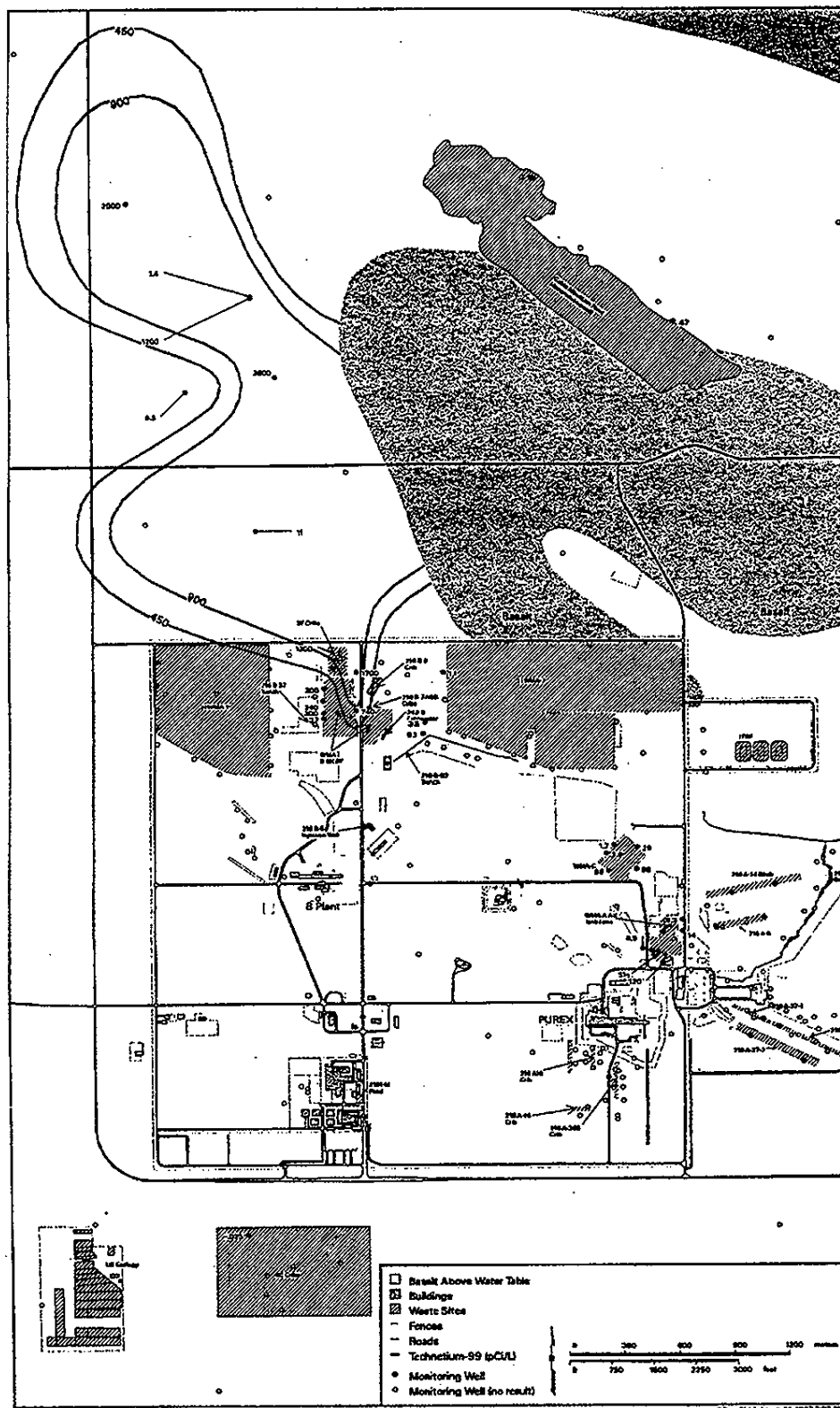
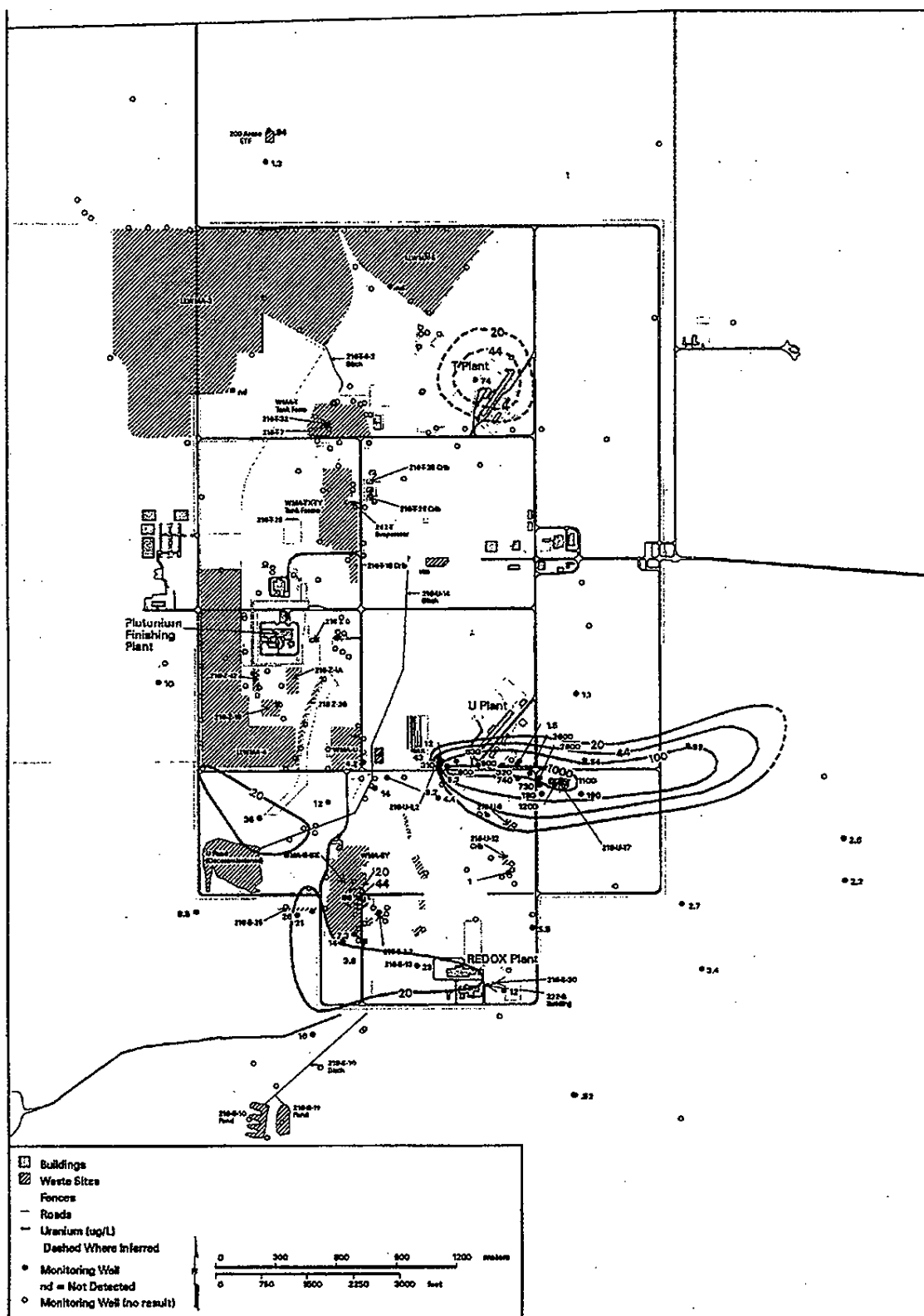


Figure B-6. Average Fiscal Year 1996 ^{99}Tc Concentration in 200 West Area.



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Figure B-7. Average Fiscal Year 1996 Uranium Concentrations in 200 West Area.

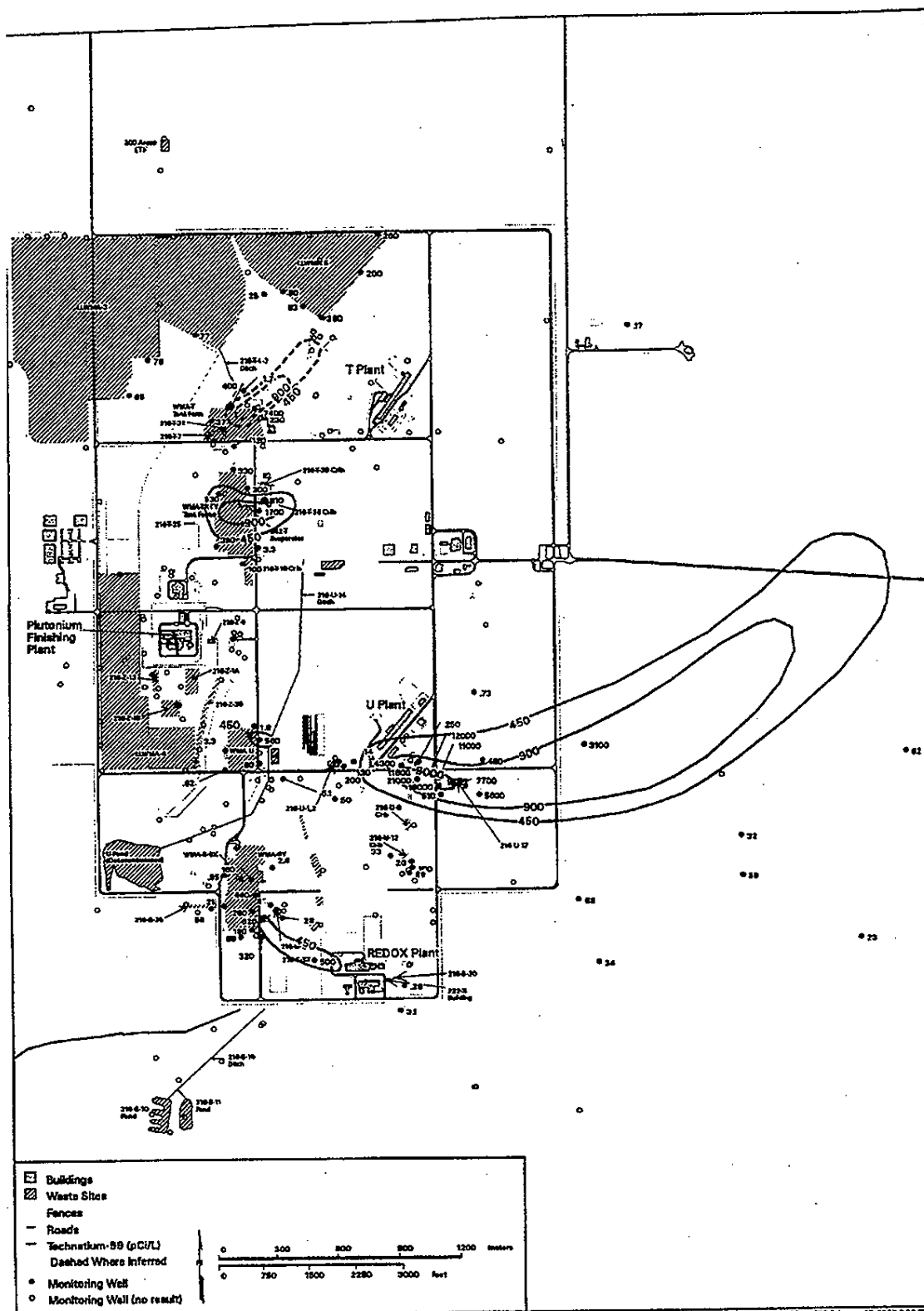


Table B-1. Summary of Estimated Recharge from Lysimeter Facilities at the Hanford Site (after Gee et al. 1992).

Facility ^a	Soil/vegetation	Time	Recharge Estimate		Ref. ^b
			(mm/yr)	(% of Precip.)	
200 East	Sand/tumbleweed	1971-1985	<2	<1	1
200 East	Sand/bare	1988-1989	90	43	2
BWTF	Sand/bare	1985-1986	111	48	2
BWTF	Sand/bare	1986-1987	102	55	2
BWTF	Sand/bare	1987-1988	40	29	2
BWTF	Sand/bare	1988-1989	42	24	2
BWTF	Sand/cheatgrass	1984-1986	62	35	3
BWTF	Sand/tumbleweed	1986-1987	1	5	2
BWTF	Sand/tumbleweed	1987-1988	0 ^c	0	2
BWTF	Sand/tumbleweed	1988-1989	10	6	2
ALE	Silt loam/sagebrush	1986-1990	0 ^c	0	4
ALE	Silt loam/bunchgrass	1986-1990	0 ^c	0	4

^a200 East = 18-m-deep, closed-bottom lysimeter

BWTF = Buried Waste Test Facility-300 Area

ALE = Arid Lands Ecology Reserve Lysimeters

STLF = Small Tube Lysimeter Facility

^b1 - Routson and Johnson (1990)

2 - Rockhold et al. (1990)

3 - Gee (1987)

4 - Gee et al. (1991)

5 - Campbell et al. (1991)

6 - Waugh et al. (1991)

^cZero value indicates that no drainage occurred from lysimeters.

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis					soil type #	Formation	Alpha (1/cm)	n	Theta _t	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay									
200-BP-1 ^{2,4}	1-0526	299-E33-38	1.9	47	18	8	27	0	sandy gravel (5)	Hanford Gravel	0.0164	1.5448	0.0229	0.2144	2.00E-05	split- spoon	Hoffman 1992
	1-0527	299-E33-38	15.1	42	50	8	0	0	sandy gravel (6)	Hanford Gravel	0.0255	1.6222	0.015 ^f	0.0773	5.70E-05	split- spoon	Relyea 1995
	1-0528	299-E33-38	51.0	42	50	8	0	0	sandy gravel (6)	Hanford Sand	0.0045	1.8509	0.0105	0.0746	5.00E-04	split- spoon	"
	1-0529	299-E33-38	62.3	79	14	7	0	0	sandy gravel (6)	Hanford Gravel	0.0026	1.4909	0.0000	0.0557	4.20E-03	split- spoon	"
	1-0530	299-E33-38	57.1	0	60	35	5	0	sand (2)	Hanford Sand	0.0123	1.6899	0.0098	0.2663	7.10E-05	split- spoon	"
	1-0531	299-E33-38	57.9	---	---	N/A	---	---	sand (2)	Hanford Sand	0.0017	1.8438	0.0400 ^f	0.4863	2.10E-06	split- spoon	"
	1-0550	299-E33-40	14.0	63	32	5	0	0	sandy gravel (6)	Hanford Gravel	0.0037	1.4567	0.0000	0.0757	6.00E-04	split- spoon	"
	1-1133	216-B-61A	4.1	76	13	11	0	0	sandy gravel (6)	Hanford Gravel	0.0028	1.8847	0.0162	0.0781	1.80E-03	split- spoon	"
	1-1134	216-B-61A	5.8	55	24	13	8	0	sandy gravel (5)	Hanford Gravel	0.0034	1.6905	0.0322	0.1409	2.80E-03	split- spoon	"
	1-1136	216-B-61A	7.0	68	20	12	0	0	sandy gravel (6)	Hanford Gravel	0.0056	1.4945	0.0187	0.1043	4.00E-04	split- spoon	"
	1-1137	216-B-61A	8.8	38	49	13	0	0	sandy gravel (5)	Hanford Gravel	0.0139	1.4207	0.0210	0.1542	1.80E-05	split- spoon	"
	2-2244	216-B-49A	26.5	1	49	48	2	0	sand (2)	Hanford Sand	0.0135	2.0185	0.0270	0.2687	4.60E-05	split- spoon	"
	2-2253	216-B-49A	35.5	2	85	13	0	0	sand (2)	Hanford Sand	0.0205	1.7138	0.0308	0.2284	8.80E-05	split- spoon	"
	2-2258	216-B-43A	41.3	1	84	15	0	0	sand (2)	Hanford Sand	0.0373	1.7815	0.0271	0.2306	2.80E-05	split- spoon	"
	2-2261	216-B-49A	48.6	12	76	12	0	0	gravelly sand (4)	Hanford Sand	0.0410	1.6885	0.0303	0.2026	1.80E-04	split- spoon	"
	2-2271	216-B-57A	60.5	50	28	14	6	2	sandy gravel (5)	Hanford Gravel	0.0074	1.4319	0.0145	0.1636	1.40E-05	split- spoon	"
	2-2283	216-B-57A	13.9	6	83	11	0	0	sand (2)	Hanford Sand	0.0298	1.6757	0.0269	0.2005	2.10E-05	split- spoon	"
	2-2286	216-B-49A	14.9	0	4	92	3	1	sand (2)	Hanford Sand	0.0077	3.0137	0.0569	0.4712	6.30E-05	split- spoon	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis					soil type #	Formation	Alpha (1/cm)	n	Theta _a	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay									
200-BP-1 ^{2,4} (cont.)	2-2289	216-B-43A	51.4	4	84	12	0	0	sand (2)	Hanford Sand	0.0131	1.6351	0.0409	0.1968	1.30E-04	split-spoon	"
	2-2294	216-B-43A	61.4	39	33	17	7	4	sandy gravel (5)	Hanford Gravel	0.0051	1.4514	0.0066	0.2006	4.40E-05	split-spoon	"
	2-2297	216-B-57A	65.4	80	20	0	0	0	sandy gravel (6)	Hanford Gravel	0.0059	1.8562	0.0074	0.0641	4.10E-04	split-spoon	"
218-W-5 ^{2,4}	0-073	299-W7-9	20.3	0	27	54	10	9	loamy sand (1)	Hanford sand	0.0008	1.9785	0.0600 ^f	0.4134	N/A	split-spoon	"
	0-082	299-W7-9	24.5	2	38	47	8	5	sand (2)	Plio-Pleistocene	0.0064	1.7084	0.1483	0.3336	6.30E-04	split-spoon	"
	0-085	299-W7-9	26.9	0	50	37	5	8	sand (2)	Plio-Pleistocene	0.0049	2.1261	0.0578	0.2105	1.30E-04	split-spoon	"
	0-101	299-W7-9	31.8	0	85	8	2	5	sand (2)	Upper Ringold	0.0695	1.4447	0.0228	0.2082	2.10E-04	split-spoon	"
	0-104	299-W7-9	34.2	0	72	24	3	1	sand (2)	Upper Ringold	0.0849	1.3106	0.0000	0.2082	1.10E-03	split-spoon	"
	5-0001	299-W7-9	21.6	4	4	79	8	5	sand (2)	Palouse paleosol	0.0057	2.8152	0.0200 ^f	0.3727	1.40E-04	split-spoon	Relyea 1995
	5-0002	299-W7-9	24.9	2	38	47	8	5	sand (2)	Plio-Pleistocene	0.0039	1.9321	0.0678	0.3454	1.32E-04	split-spoon	"
	5-0003	299-W7-9	43.2	0	74	22	1	3	sand (2)	Upper Ringold	0.0414	1.9382	0.0211	0.3004	1.80E-04	split-spoon	"
	5-0004	299-W7-9	30.3	0	58	30	7	5	sand (2)	Upper Ringold	0.0102	1.5737	0.0267	0.3256	1.65E-04	split-spoon	"
	5-0005	299-W7-9	21.1	0	0	73	22	5	sandy loam (1)	Palouse paleosol	0.0069	2.2430	0.0400 ^f	0.3851	6.70E-05	split-spoon	"
	5-0006	299-W7-9	19.9	0	27	54	10	9	loamy sand (1)	Hanford sand	0.0064	2.2593	0.0584	0.3274	N/A	split-spoon	"
	5-0007	299-W7-9	40.3	0	80	13	5	2	sand (2)	Upper Ringold	0.1308	1.7017	0.0231	0.3502	3.00E-03	split-spoon	"
	W7-2-65	299-W07-02	19.8	35	38	11	16	0	silty sandy gravel (3)	Plio-Pleistocene	0.02102	1.4563	0.064	0.3752	6.80E-02	split-spoon	Bjornstad, 1990
	218-W-5 1,5																

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis					soil type #	Formation	Alpha (1/cm)	n	Theta _r	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay									
218-W-5 1,5 (cont.)	W7-2-94	299-W07-02	28.6	48	39	7	6	0	sandy gravel (5)	Upper Ringold	0.0557	1.9669	0.0223	0.2168	3.70E-02	split-spoon	"
	W7-2-154	299-W07-02	46.9	32	36	15	17	0	silty sandy gravel (3)	Middle Ringold	0.1027	1.3782	0.0150 ^f	0.3071	2.10E-02	split-spoon	"
	W7-2-219	299-W07-02	66.8	39	35	18	8	0	sandy gravel (5)	Middle Ringold	0.068	1.7788	0.0617	0.1594	2.70E-03	split-spoon	"
	W10-13-45	299-W10-13	13.7	0	62	33	5	0	sand (2)	Hanford Sand	0.0408	2.0672	0.0396	0.3915	5.80E-02	split-spoon	"
	W10-13-80	299-W10-13	24.4	64	25	6	5	0	sandy gravel (5)	Hanford Gravel	0.2758	1.3718	0.0367	0.1781	2.70E-02	split-spoon	"
241-T-106 ^{2,4}	3-0210	299-W10-196	3.1	48	30	22	0	0	sandy gravel (5)	Hanford gravel	0.0115	2.2692	0.0450	0.1854	1.00E-03	split-spoon	Relyea, 1995
	3-0213	299-W10-196	5.6	31	33	36	0	0	gravelly sand (4)	Hanford gravel	0.0040	2.4233	0.0494	0.2083	1.02E-03	split-spoon	"
	3-0279	299-W10-196	1.8	46	32	20	2	0	sandy gravel (5)	Hanford gravel	0.0061	2.1046	0.0337	0.1492	N/A	split-spoon	"
	3-0589	299-W10-196	25.5	2	56	42	0	0	sand (2)	Hanford sand	0.0040	2.0685	0.0575	0.3443	1.38E-05	split-spoon	"
	3-0667	299-W10-196	42.2	80	13	7	0	0	sandy gravel (6)	Middle Ringold	0.0115	1.3466	0.0000	0.0718	2.83E-05	split-spoon	"
	3-0668	299-W10-196	38.9	63	15	12	10	0	sandy gravel (5)	Middle Ringold	0.0023	1.5765	0.0100 ^f	0.1470	1.60E-03	split-spoon	"
	3-0682	299-W10-196	46.1	0	54	35	10	1	sand (1)	Middle Ringold	0.0128	2.0864	0.0519	0.4334	4.57E-05	split-spoon	"
	3-0688	299-W10-196	48.5	0	38	28	28	6	sandy loam (1)	Middle Ringold	0.0036	1.6568	0.0302	0.3230	N/A	split-spoon	"
	3-0689	299-W10-196	52.2	0	36	30	25	9	sandy loam (1)	Middle Ringold	0.0022	1.6651	0.0300 ^f	0.3208	N/A	split-spoon	"
	3-0690	299-W10-196	53.7	0	39	31	23	7	sandy loam (1)	Middle Ringold	0.0042	1.6376	0.0564	0.3683	6.55E-06	split-spoon	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis					soil type #	Formation	Alpha (1/cm)	n	Theta _t	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay									
AP Tank ^{1,5}	241-APIG	N/A	N/A	38	58	3	1	0	sandy gravel (5)	Hanford sand	0.1018	2.9473	0.0212	0.2599	1.24E-03	excavation	Heller, 1989
	241-AP-2	N/A	N/A	0	68	26	3	3	sand (2)	Hanford sand	0.0309	3.0872	0.0994	0.519	5.97E-04	excavation	"
	241-AP-3	N/A	N/A	0	85	12	2	1	sand (2)	Hanford sand	0.0494	3.4878	0.062	0.4348	8.10E-04	excavation	"
	241-AP-4G	N/A	N/A	10	83	5	2	0	sand (2)	Hanford sand	0.0698	2.6694	0.0416	0.4162	1.87E-03	excavation	"
	241-AP-5	N/A	N/A	0	7	49	36	8	sandy loam (1)	Hanford sand	0.0108	1.4367	0.0268	0.4293	4.94E-05	excavation	"
	241-AP-6	N/A	N/A	1	36	43	14	6	loamy sand (1)	Hanford sand	0.0053	1.9484	0.068	0.4049	8.60E-05	excavation	"
C-018-H ^{2,4}	2-1169	699-48-77	8.1	14	40	44	2	0	gravelly sand (4)	Plio-Pleistocene	0.0076	2.5367	0.0569	0.3069	5.30E-03	split-spoon	Relyea, 1995
	2-1170	699-48-77	8.9	22	42	33	3	0	gravelly sand (4)	Plio-Pleistocene	0.0048	1.9770	0.0635	0.3011	1.30E-04	split-spoon	"
	2-1176	699-48-77	13.0	1	79	20	0	0	sand (2)	Plio-Pleistocene	0.0223	1.7587	0.0262	0.2230	2.00E-02	split-spoon	"
	2-1181	699-48-77	14.1	8	82	10	0	0	sand (2)	Plio-Pleistocene	0.0728	1.3096	0.0230	0.2147	8.20E-03	split-spoon	"
	2-1431	699-48-77A	20.6	---	---	N/A	---	---	sand (2)	Plio-Pleistocene	0.0227	1.5859	0.0432	0.2346	1.80E-02	split-spoon	"
	2-1432	699-48-77A	27.6	51	30	15	4	0	sandy gravel (5)	Middle Ringold	0.0083	1.5938	0.0191	0.1128	1.40E-02	split-spoon	"
ERDF ^{2,6}	4-0637	699-36-63A	74.9	---	---	N/A	---	---	sand (2)	Hanford sand	0.0261	3.2937	0.0278	0.3743	N/A	split-spoon	Relyea 1995
	4-0642	699-35-69A	25.7	0	60	30	10	0	sand (2)	Hanford sand	0.0119	1.6727	0.0566	0.3513	N/A	split-spoon	Weekes and Borghese 1994
	4-0644	699-35-69A	49.8	0	27	56	12	5	loamy sand (1)	Hanford sand	0.0069	2.2673	0.0828	0.3922	N/A	split-spoon	"
	4-0791	699-35-65A	63.2	0	50	50	0	0	sand (2)	Hanford sand	0.0217	2.4513	0.0303	0.3371	N/A	split-spoon	"
	4-0792	699-35-65A	75.4	70	21	8	1	0	sandy gravel (6)	Middle Ringold	0.0276	1.6636	0.0091	0.0825	N/A	split-spoon	"
	4-0855	699-35-66B	12.2	0	7	83	5	5	sand (2)	Hanford sand	0.0088	3.2652	0.0689	0.3936	N/A	split-spoon	"
	4-0973	699-35-68A	37.0	0	21	64	12	3	loamy sand (1)	Hanford sand	0.0169	2.0085	0.0190 ^f	0.3525	1.27E-04	split-spoon	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis				soil type #	Formation	Alpha (1/cm)	n	Theta _t	Theta _a	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt									
ERDF ^{2,6} (cont.)	4-0983	699-35-68A	82.9	17	35	42	4	2	gravelly sand (4)	0.0156	2.0226	0.0100 ^f	0.3373	5.43E-05	split-spoon	"
	4-1011	699-35-69A	73.0	0	4	60	28	8	loamy sand (1)	0.0042	1.5218	0.0450 ^f	0.4913	1.00E-05	split-spoon	"
	4-1012	699-35-69A	73.9	50	20	20	7	3	sandy gravel (5)	0.0062	1.6452	0.0100 ^f	0.1643	5.10E-05	split-spoon	"
	4-1013	699-35-69A	77.9	77	6	12	3	2	sandy gravel (5)	0.0064	1.6574	0.0214	0.1397	1.90E-07	split-spoon	"
	4-1056	699-32-72B	61.7	0	6	88	4	2	sand (2)	0.0071	2.7253	0.0350 ^f	0.4288	N/A	split-spoon	"
	4-1057	699-32-72B	49.5	0	2	68	24	6	loamy sand (1)	0.0046	2.2861	0.0890	0.4877	N/A	split-spoon	"
	4-1058	699-32-72B	64.7	0	1	41	43	15	loam (1)	0.0029	1.5267	0.1023	0.5661	N/A	split-spoon	"
	4-1076	699-35-61A	76.4	0	75	25	0	0	sand (2)	0.0235	2.0956	0.0265	0.3433	N/A	split-spoon	"
	4-1079	699-35-61A	90.9	65	24	11	0	0	sandy gravel (5)	0.0073	1.6668	0.0295	0.1236	1.30E-03	split-spoon	"
	4-1080	699-35-61A	93.5	63	24	10	3	0	sandy gravel (5)	0.0062	1.6601	0.0302	0.1316	3.30E-06	split-spoon	"
FLTF ^{1,5}	D02-10	N/A	<6.1	0	2	54	34	10	sandy loam (1)	0.0049	1.9773	0.0778	0.4531	1.20E-04	excavation	Gee et al., 1989
	D02-16	N/A	<6.1	0	2	63	25	10	sandy loam (1)	0.0035	2.4632	0.0820 ^f	0.4630	1.20E-04	excavation	Volk, 1993
	D04-04	N/A	<6.1	0	4	58	28	10	sandy loam (1)	0.0072	1.6501	0.0700 ^f	0.4508	1.20E-04	excavation	"
	D04-10	N/A	<6.1	0	3	58	30	9	sandy loam (1)	0.0066	1.7574	0.0800 ^f	0.4428	2.90E-04	excavation	"
	D05-03	N/A	<6.1	0	4	63	23	10	sandy loam (1)	0.0055	1.8647	0.0860 ^f	0.4332	2.90E-04	excavation	"
	D07-04	N/A	<6.1	0	3	58	30	9	sandy loam (1)	0.0051	1.9424	0.0820 ^f	0.4435	1.20E-04	excavation	"
	D08-15	N/A	<6.1	0	2	57	31	10	sandy loam (1)	0.0059	1.8533	0.0850 ^f	0.4543	1.20E-04	excavation	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis					soil type #	Formation	Alpha (1/cm)	n	Theta _a	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay									
FLTFF ^{1,5} (cont.)	D09-01	N/A	<6.1	0	3	51	37	9	sandy loam (1)	Warden silt loam	0.0066	1.7677	0.0800 ^f	0.4544	1.20E-04	excavation	"
	D09-02	N/A	<6.1	0	2	57	31	10	sandy loam (1)	Warden silt loam	0.0069	1.8498	0.0825	0.4559	1.20E-04	excavation	"
	D09-05	N/A	<6.1	0	7	60	29	4	sandy loam (1)	Warden silt loam	0.0088	1.6183	0.0681	0.4461	2.90E-04	excavation	"
	D10-04	N/A	<6.1	0	6	59	30	5	sandy loam (1)	Warden silt loam	0.0064	1.7899	0.0850 ^f	0.4481	1.20E-04	excavation	"
	D11-06	N/A	<6.1	0	4	57	33	6	sandy loam (1)	Warden silt loam	0.0061	1.8575	0.0850 ^f	0.4308	1.20E-04	excavation	"
	D11-08	N/A	<6.1	0	5	58	32	5	sandy loam (1)	Warden silt loam	0.0061	1.7567	0.0850 ^f	0.4312	1.20E-04	excavation	"
	D12-14	N/A	<6.1	0	3	52	34	11	sandy loam (1)	Warden silt loam	0.0063	1.7576	0.0980 ^f	0.4686	1.20E-04	excavation	"
	D13-08	N/A	<6.1	0	4	52	35	9	sandy loam (1)	Warden silt loam	0.0070	1.7877	0.0820 ^f	0.4513	1.20E-04	excavation	"
	D14-04	N/A	<6.1	0	3	56	36	5	sandy loam (1)	Warden silt loam	0.0065	1.8553	0.0837	0.4586	1.20E-04	excavation	"
	5A	299-E25-234	1.5	1	73	17	5	4	sand (2)	Eolian sand	0.1480	1.3087	0.0187	0.4131	5.73E-04	split- spoon	Rockhold et al. 1993
	5B	299-E25-234	1.5						sand (2)	Eolian sand	0.0211	1.5360	0.0336	0.3367	5.73E-04	split- spoon	"
	19A	299-E25-234	5.8	2	28	53	12	5	loamy sand (1)	Eolian sand	0.3870	1.2615	0.0461	0.4860	8.88E-04	split- spoon	"
	19B	299-E25-234	5.8						loamy sand (1)	Eolian sand	0.2729	1.5326	0.0363	0.5026	8.88E-04	split- spoon	"
	25A	299-E25-234	7.6	0	49	36	10	5	loamy sand (1)	Eolian sand	0.0473	2.0595	0.0539	0.4407	1.80E-03	split- spoon	"
	25B	299-E25-234	7.6						loamy sand (1)	Eolian sand	0.0519	1.3421	0.0342	0.5228	1.80E-03	split- spoon	"
Grout ^{1,5}	25C	299-E25-234	7.6						loamy sand (1)	Eolian sand	0.0287	1.3529	0.0280 ^f	0.5062	1.80E-03	split- spoon	"
	25D	299-E25-234	7.6						loamy sand (1)	Eolian sand	0.0700	1.8780	0.0800 ^f	0.4822	1.80E-03	split- spoon	"
	29A	299-E25-234	8.8	0	60	31	6	3	sand (2)	Eolian sand	0.2718	1.1928	0.0000	0.4341	2.41E-05	split- spoon	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis				soil type #	Formation	Alpha (1/cm)	n	Theta _a	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	es	fs	silt	clay								
Grout ^{1,3} (cont.)	29B	299-E25-234	8.8						sand (2)	0.1033	1.2242	0.0000	0.4387	2.41E-05	split-spoon	"
	37A	299-E25-234	11.3	1	43	39	10	7	loamy sand (1)	0.0775	1.2921	0.0703	0.5114	5.77E-04	split-spoon	"
	37B	299-E25-234	11.3						loamy sand (1)	0.0914	1.3319	0.0844	0.5304	5.77E-04	split-spoon	"
	46A	299-E25-234	14	0	73	22	2	3	sand (2)	0.2923	1.3658	0.0000	0.4581	2.99E-04	split-spoon	"
	46B	299-E25-234	14						sand (2)	0.0613	1.4343	0.0000	0.3708	2.99E-04	split-spoon	"
	54A	299-E25-234	16.5	1	51	32	9	7	loamy sand (1)	0.1524	1.4137	0.0262	0.4488	1.38E-05	split-spoon	"
	54B	299-E25-234	16.5						loamy sand (1)	0.1451	1.4419	0.0216	0.4543	1.38E-05	split-spoon	"
	69A	299-E25-234	21	3	71	19	5	2	sand (2)	0.3357	1.2658	0.0000	0.3721	1.21E-03	split-spoon	"
	69B	299-E25-234	21						sand (2)	0.2269	1.6572	0.0288	0.4042	1.21E-03	split-spoon	"
	83A	299-E25-234	25.3	4	70	19	5	2	sand (2)	0.2979	1.3300	0.0070 ^f	0.3915	1.78E-04	split-spoon	"
	83B	299-E25-234	25.3						sand (2)	0.1157	1.4027	0.0070 ^f	0.3696	1.78E-04	split-spoon	"
	99A	299-E25-234	30.2	0	34	60	4	2	sand (2)	0.7417	1.2557	0.0000	0.3692	2.24E-04	split-spoon	"
	99B	299-E25-234	30.2						sand (2)	0.3823	1.3262	0.0100	0.3765	2.24E-04	split-spoon	"
	110A	299-E25-234	33.5	6	64	23	5	2	sand (2)	0.1964	1.8193	0.0324	0.4293	2.82E-04	split-spoon	"
	110B	299-E25-234	33.5						sand (2)	0.1991	1.8015	0.0326	0.4201	2.82E-04	split-spoon	"
	117A	299-E25-234	35.7	3	62	26	5	4	sand (2)	0.1114	1.6538	0.0259	0.4538	3.63E-03	split-spoon	"
	117B	299-E25-234	35.7						sand (2)	0.0230	1.5237	0.0011	0.3831	3.63E-03	split-spoon	"
	126A	299-E25-234	38.4	51	33	14	1	1	sandy gravel (5)	0.9193	1.3700	0.0106	0.1755	1.98E-03	split-spoon	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis				soil type #	Formation	Alpha (1/cm)	n	Theta _r	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay								
Grout ^{1,5} (cont.)	126B	299-E25-234	38.4						sandy gravel (5)	0.4783	1.4639	0.0127	0.1823	1.98E-03	split- spoon	"
	133A	299-E25-234	40.5	30	33	25	9	3	silty sandy gravel (3)	0.0163	1.3134	0.0000	0.1877	2.76E-05	split- spoon	"
	133B	299-E25-234	40.5						silty sandy gravel (3)	0.0331	1.2555	0.0000	0.1871	2.76E-05	split- spoon	"
Injection ^{2,4}	1-1417	299-E24-95	1.8	1	23	68	7	1	sand (2)	0.0051	1.6827	0.0200 ^f	0.3501	1.40E-04	core barrel	Relyea 1995
	1-1418	299-E24-95	3.0	18	56	26	0	0	gravelly sand (4)	0.0310	1.5289	0.0336	0.2152	1.80E-04	core barrel	"
	1-1419	299-E24-95	4.9	2	88	10	0	0	sand (2)	0.4984	1.4065	0.0090	0.3013	3.20E-04	core barrel	"
	2-1636	299-E24-95	4.9	2	84	14	0	0	sand (2)	0.1385	1.7079	0.0228	0.3073	8.70E-04	core barrel	"
	2-1637	299-E24-79	9.8	0	80	20	0	0	sand (2)	0.0760	1.8863	0.0248	0.3026	4.20E-03	core barrel	"
	2-1638	299-E24-79	12.2	0	81	19	0	0	sand (2)	0.1016	1.3365	0.0000	0.2720	5.80E-03	core barrel	"
	2-1639	299-E24-79	18.3	0	93	7	0	0	sand (2)	0.3333	1.5801	0.0179	0.3206	1.30E-03	core barrel	"
	2-2225	299-E24-92	9.8	0	80	20	0	0	sand (2)	0.0242	4.1695	0.0335	0.3309	5.50E-03	core barrel	"
	2-2226	299-E24-92	15.2	6	90	4	0	0	sand (2)	0.5282	1.4780	0.0168	0.2861	1.50E-02	core barrel	"
	2-2227	299-E24-92	18.3	2	92	6	0	0	sand (2)	0.1216	1.7364	0.0154	0.3271	8.70E-03	core barrel	"
	2-2228	299-E24-95	15.2	1	97	2	0	0	sand (2)	0.8612	1.4523	0.0092	0.2925	2.10E-02	core barrel	"
	2-2229	299-E24-95	18.3	1	94	5	0	0	sand (2)	0.1358	1.8345	0.0197	0.3070	6.40E-03	core barrel	"
	2-2230	299-E24-79	1.8	2	32	52	11	3	sand (2)	0.0066	2.1407	0.0608	0.3309	2.30E-04	core barrel	"
	2-2231	299-E24-79	3.0	12	52	36	0	0	gravelly sand (4)	0.0063	1.7824	0.0685	0.2811	7.50E-03	core barrel	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis				soil type #	Formation	Alpha (1/cm)	n	Theta _r	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay								
Injection ^{2,4} (cont)	2-2232	299-E24-79	4.9	4	88	8	0	0	sand (2)	Hanford sand	2.0873	0.0279	0.2450	4.10E-02	core barrel	"
	2-2233	299-E24-79	7.9	2	90	8	0	0	sand (2)	Hanford sand	1.4491	0.0130	0.2906	1.70E-02	core barrel	"
	2-2234	299-E24-79	11.0	0	86	14	0	0	sand (2)	Hanford sand	1.5548	0.0123	0.2782	2.10E-02	core barrel	"
U.S. Ecology ^{1,3} MW-5	50	699-35-58	15.2	1	75	18	6	0	sand (2)	Hanford sand	2.6308	0.0367	0.3309	3.53E-02	split-spoon	Bergeron et al. 1987
	70	699-35-58	21.3	0	38	51	11	0	sand (2)	Hanford sand	4.7700	0.0300 ^f	0.4431	1.57E-03	split-spoon	"
	90	699-35-58	27.4	0	81	15	4	0	sand (2)	Hanford sand	3.0831	0.0250	0.3854	2.26E-03	split-spoon	"
	130	699-35-58	39.6	0	28	68	4	0	sand (2)	Hanford sand	4.9138	0.0250 ^f	0.4163	4.42E-02	split-spoon	"
	170	699-35-58	51.8	0	52	42	6	0	sand (2)	Hanford sand	3.5355	0.0334	0.3927	3.81E-03	split-spoon	"
	190	699-35-58	57.9	1	84	11	4	0	sand (2)	Hanford sand	2.8261	0.0200 ^f	0.4532	5.78E-03	split-spoon	"
	210	699-35-58	64.0	3	85	8	4	0	sand (2)	Hanford sand	2.2980	0.0321	0.2724	5.42E-03	split-spoon	"
U.S. Ecology ^{1,3} MW-8	230	699-35-58	70.1	0	77	18	5	0	sand (2)	Hanford sand	3.1424	0.0100 ^f	0.4193	5.31E-03	split-spoon	"
	270	699-35-58	82.3	0	62	23	15	0	loamy sand (1)	Hanford sand	1.5601	0.0200 ^f	0.3270	5.54E-04	split-spoon	"
	300	699-35-58	91.4	59	19	13	9	0	sandy gravel (5)	Middle Ringold	1.6304	0.0123	0.1190	7.66E-04	split-spoon	"
	14.5	699-36-58B	4.4	0	78	18	4	0	sand (2)	Hanford sand	3.1199	0.0395	0.4308	1.70E-03	split-spoon	"
	145	699-36-58B	44.2	0	2	58	40	0	sandy loam (1)	Hanford sand	2.8937	0.0200 ^f	0.4233	8.86E-04	split-spoon	"
U.S. Ecology ^{1,3} MW-10	185	699-36-58B	56.4	22	68	7	3	0	gravelly sand (4)	Hanford sand	2.0899	0.0288	0.3074	7.19E-03	split-spoon	"
	45	699-36-58A	13.7	1	69	20	10	0	sand (2)	Hanford sand	2.2830	0.0382	0.3385	5.31E-03	split-spoon	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis					soil type #	Formation	Alpha (1/cm)	n	Theta _v	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay									
U.S. Ecology ^{1,3} MW-10 (cont)	86	699-36-58A	26.2	0	55	38	7	0	sand (2)	Hanford sand	0.0355	2.0852	0.0314	0.3822	1.97E-02	split-spoon	"
	105	699-36-58A	32.0	1	62	24	13	0	loamy sand (1)	Hanford sand	0.0233	1.9835	0.0408	0.3267	1.73E-02	split-spoon	"
	125	699-36-58A	38.1	1	59	30	10	0	sand (2)	Hanford sand	0.0210	2.8388	0.0429	0.3638	4.39E-03	split-spoon	"
	165	699-36-58A	50.3	1	59	30	10	0	sand (2)	Hanford sand	0.0186	3.4294	0.0373	0.3233	6.63E-03	split-spoon	"
	195	699-36-58A	59.4	24	57	13	6	0	gravelly sand (4)	Hanford sand	0.0312	2.0934	0.0298	0.2621	2.65E-03	split-spoon	"
	205	699-36-58A	62.5	10	71	12	7	0	gravelly sand (4)	Hanford sand	0.0503	1.7946	0.0258	0.2969	6.63E-03	split-spoon	"
	245	699-36-58A	74.7	0	71	20	9	0	sand (2)	Hanford sand	0.0319	2.3729	0.0321	0.3686	7.39E-03	split-spoon	"
	265	699-36-58A	80.8	0	64	25	11	0	sand (1)	Hanford sand	0.0259	2.5903	0.0160 ^f	0.3589	2.65E-03	split-spoon	"
	285	699-36-58A	86.9	0	64	26	10	0	sand (2)	Hanford sand	0.0282	2.6922	0.0170 ^f	0.3648	3.54E-03	split-spoon	"
	300	699-36-58A	91.4	0	71	22	7	0	sand (2)	Hanford sand	0.0291	3.1582	0.0281	0.3668	4.42E-03	split-spoon	"
U.S. Ecology ^{1,3} VOC ^{2,4}	3-0647 ^x	299-W18-246	42.9	0	2	78	14	6	loamy sand (1)	Plio-Pleistocene	0.0051	2.0531	0.0400 ^f	0.4995	2.00E-04	split-spoon	Relyea 1995
	3-0648	299-W18-246	59.6	62	18	20	0	0	sandy gravel (5)	Middle Ringold	0.0124	1.6450	0.0000	0.1462	8.70E-03	split-spoon	"
	3-0649	299-W18-247	41.1	0	10	38	40	12	loam (1)	Plio-Pleistocene	0.0010	1.7024	0.0600 ^f	0.5331	N/A	split-spoon	"
	3-0650	299-W18-247	45.1	0	46	28	15	11	sandy loam (1)	Plio-Pleistocene	0.0120	1.5539	0.2412	0.6306	2.60E-07	split-spoon	"
	3-0651	299-W18-247	46.9	0	58	24	9	9	loamy sand (1)	Plio-Pleistocene	0.0286	1.9721	0.1006	0.3728	9.40E-03	split-spoon	"
	3-0652	299-W18-248	38.4	0	40	52	4	4	sand (2)	Hanford Sand	0.0092	1.8848	0.0300 ^f	0.3586	3.70E-04	split-spoon	"
	3-0653	299-W18-248	42.5	0	24	54	14	8	loamy sand (1)	Plio-Pleistocene	0.0067	1.8378	0.1096	0.4223	5.80E-06	split-spoon	"
	3-0654	299-W15-216	35.6	59	30	3	4	4	sandy gravel (5)	Plio-Pleistocene	0.0119	1.2618	0.0186	0.1933	2.70E-04	split-spoon	"

Table B-2. Summary of Soil Physical and Hydraulic Parameters in the 200 Areas.

Site	Sample no.	Borehole	Depth (m)	Sieve analysis				soil type #	Formation	Alpha (1/cm)	n	Theta _t	Theta _s	K _s (cm/s)	Sampling technique	Source
				gr	cs	fs	silt	clay								
U.S. Ecology ^{1,3} VOC ^{2,4} (cont.)	3-0655	299-W15-216	36.9	34	28	8	24	6	silty sandy gravel (3)	Upper Ringold	1.6285	0.0559	0.2625	1.58E-04	split-spoon	"
	3-0656	299-W15-216	39.0	42	40	18	0	0	sandy gravel (5)	Middle Ringold	1.3941	0.0090	0.1814	1.36E-02	split-spoon	"
	3-0657	299-W15-217	37.4	34	38	10	10	8	silty sandy gravel (3)	Hanford	1.3692	0.0469	0.2505	2.67E-04	split-spoon	"
U.S. Ecology ^{1,3} W-049-H ^{2,4}	2-2865 ^x	699-42-37	38.7	0	22	58	14	6	loamy sand (1)	Lower Ringold	2.0069	0.1612	0.5868	2.30E-06	split-spoon	Delaney 1992
	2-3084	699-41-39	24.7	82	14	4	0	0	sandy gravel (6)	Upper Ringold	1.5700	0.0125	0.0579	1.30E-01	split-spoon	"
	2-3085 ^x	699-41-35	31.5	0	55	25	10	10	sandy loam (1)	Lower Ringold	1.2598	0.2705	0.6772	1.40E-08	split-spoon	"
	2-3088	699-42-37	4.6	65	20	12	3	0	sandy gravel (6)	Hanford	1.5977	0.0197	0.1071	1.30E-03	split-spoon	"
	2-3089 ^x	699-42-37	28.3	0	35	30	27	8	sandy loam (1)	Hanford	1.3657	0.1808	0.5336	3.20E-07	split-spoon	"
	3-0001	699-40-36	29.3	68	19	6	7	0	sandy gravel (5)	Hanford	1.5556	0.0156	0.1128	1.82E-04	split-spoon	"
	3-0003	699-40-36	65.8	65	21	14	0	0	sandy gravel (5)	Basal Ringold	1.4011	0.0538	0.1953	6.30E-07	split-spoon	"

soil category:

- (1) - SS, sand mixed with finer fraction
- (2) - S, sand
- (3) - SSG, sand and gravel mixed with finer fraction
- (4) - GS, gravelly sand
- (5) - SG1, sandy gravel with gravel content approximately <60 percent
- (6) - SG2, sandy gravel with gravel content approximately >60 percent

^f signifies that the residual moisture content has been fixed to improve the curve fit through the measured data^x sample containing swelling clay.¹ K_s measured by falling head permeameter.² K_s measured by constant head permeameter.

Moisture-Retention Data Measurement

³ 0 to -60 cm, hanging water column; -100 to -15300 cm, pressure plate extraction (Klute 1986).⁴ 0 to -1000 cm, Tempe cell; -500 to -15300 cm, pressure plate extraction.⁵ 0 to -150 cm, hanging water column; -350 to -15300 cm, pressure plate extraction; <-15300 cm, thermocouple psychrometer (Rawlins and Campbell 1986).⁶ 0 to -1000 cm, Tempe cell; -500 to -10000 cm, pressure plate extraction; <-10000 cm, thermocouple psychrometer.

Table B-3. Statistical Parameters Used for Cumulative Distribution Function Approximation.¹

Soil category	Hydraulic properties	Lower limit	Upper limit	Transform	Statistics		
					Mean	Standard deviation	D _{max} ²
SS	θ_s^3	0.321	0.566	NO	0.438	0.059	0.103
	θ_r	0.000	0.881	SN	0.458	0.255	0.148
	α	-7.131	-0.949	LN	-4.489	1.352	0.164
	n	1.262	2.894	NO	1.824	0.344	0.064
S	K _s	-12.058	-4.057	LN	-8.487	1.813	0.144
	θ_s	0.197	0.519	NO	0.346	0.073	0.050
	θ_r	0.000	0.881	SN	0.189	0.146	0.134
	α	-5.547	-0.149	LN	-3.097	1.347	0.057
	n	-5.756	4.330	LR	-1.459	1.523	0.080
	K _s	-11.191	-2.847	LN	-6.849	2.129	0.089
SSG	θ_s	0.187	0.375	NO	0.262	0.072	0.178
	θ_r	0.000	0.064	NO	0.030	0.029	0.202
	α	-5.843	-2.276	LN	-3.957	1.166	0.153
	n	1.256	1.629	NO	1.400	0.131	0.233
	K _s	-10.854	2.995	LR	-5.262	5.499	0.198
GS	θ_s	0.203	0.334	NO	0.272	0.048	0.182
	θ_r	0.010	0.069	NO	0.040	0.019	0.226
	α	0.004	0.074	NO	0.027	0.023	0.191
	n	1.529	2.537	NO	1.994	0.315	0.176
	K _s	-7.966	2.989	LR	-1.569	3.582	0.159
SG1	θ_s	0.113	0.260	NO	0.166	0.036	0.071
	θ_r	0.000	0.062	NO	0.023	0.015	0.134
	α	-6.075	-0.084	LN	-4.086	1.550	0.232
	n	0.233	1.081	LN	0.489	0.184	0.169
	K _s	-15.476	-3.297	LN	-7.932	3.322	0.150
SG2	θ_s	-2.888	-2.234	LN	-2.590	0.216	0.226
	θ_r	0.000	0.0197	NO	0.010	0.007	0.171
	α	-5.952	-3.590	LN	-5.008	0.882	0.187
	n	1.347	1.885	NO	1.621	0.178	0.162
	K _s	-10.473	-2.040	LN	-7.137	2.332	0.145

¹The class of transforms used, in addition to normal (NO) distribution is the Johnson system as described in Carsel and Parrish (1988). The Johnson system involves three primary distribution types: lognormal (LN), log ratio (LR), and hyperbolic arcsine (SN):

$$LN: Y = \ln(X)$$

where Y denotes the transformed variable, X denotes the untransformed variable and corresponds to any of the variables θ_s , θ_r , α , n , and K_s , with limits of variation from A to B ($A < X < B$) and $U = (X - A)/(B - A)$. LR is bounded between limits A and B , whereas SN is unbounded.

$$SN: \sinh^{-1}[U] = \ln\left[U + (1 + U^2)^{\frac{1}{2}}\right]$$

$$LR: Y = \ln\left[\frac{(X - A)}{(B - X)}\right]$$

² The Kolmogorov-Smirnov (K-S) goodness-of-fit statistic D (maximum absolute deviation between the empirical and fitted CDFs) was used to select the best fit distribution among the four distributions (NO, LN, LR, SN).

³The van Genuchten model (1980) is:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + |ah|^n]^m}$$

where	θ	= volumetric moisture content,
	θ_s	= saturated moisture content,
	θ_r	= residual moisture content,
	α	= van Genuchten curve fitting parameter (1/cm),
	h	= matric potential or pressure head (-cm),
	n	= van Genuchten curve fitting parameter,
and	m	= $1 - 1/n$.

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APPENDIX C
GEOCHEMICAL FACTORS AND EFFECTS ON CONTAMINANT TRANSPORT

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APPENDIX C

GEOCHEMICAL FACTORS AND EFFECTS ON CONTAMINANT TRANSPORT

C1.0 INTRODUCTION

This document covers the processes and an empirical distribution value (a K_d value) between soil and water that normally is used in modeling. The majority of the available information is based on natural environmental conditions.

C2.0 BACKGROUND MINERALOGICAL AND CHEMICAL CHARACTERISTICS

Mineralogical-characterization data of vadose zone materials are not as extensive as particle-size data. Because reactivity of contaminants with solid phases is expected to vary as a function of particle size, the mineralogy description is organized by particle size. The mineral content of the sand-size (2 mm) and larger fractions of sediment typically is dominated by quartz and feldspar with gravels containing primarily rock fragments (Routson et al. [1979], Serne et al. [1993]). Secondary minerals include iron oxides and calcite. The minerals in these coarse fractions generally contribute little to chemical retardation except that magnetite has the potential to act as a reducing agent and calcite tends to neutralize acidic solutions.

Sand-size and smaller fractions contain 60 to 80 weight percent quartz and feldspar with up to 10 percent mica and secondary iron-bearing minerals (Routson et al. 1979; Serne et al. 1993). The mineralogy of the clay-size fraction ($<2 \mu\text{m}$) consisting of clays and hydrous oxides is reported occasionally (Routson et al. 1979; Serne et al. 1993; Serne et al. 1998). The major clay minerals, which usually compose less than 20 wt percent of the $<2 \text{ mm}$ fraction consist mostly of smectite-type clays and mica/illites with considerably smaller amounts of chlorite, vermiculite, and kaolinite. According to Serne et al. (1998), the ratio of smectites to other clays is higher in the sediments of the Ringold Formation than in those of the Hanford formation, but this conclusion is based on a small number of samples. An estimate of hydrous oxides of aluminum, iron, manganese, and silicon is reported by Serne et al. (1993); together these oxides make up less than 0.1 percent of the $<2 \text{ mm}$ fraction. This low concentration of hydrous oxides probably has little effect on contaminant sorption, but both aluminum and iron hydrous oxides, if present in higher amounts, are known to sorb metals such as lead, copper, cadmium, cobalt, and zinc and can form surface complexes with some actinides (Serne et al. 1998). The higher amounts of clay minerals have an influence on cation sorption disproportionate to their relative volume. The mica-like clays can have unique sorption sites that selectively sorb cesium, as mentioned by Tamura and Jacobs (1960) and further described in Serne et al. (1998). Together, the clay minerals and hydrous oxides account for most of the sorption capacity and selectivity for waste contaminants and consequently become an important soil parameter.

Knowing background chemical composition, including major and trace constituents, radiochemical content, and organic content of soils is required to support evaluations of contamination, as well as provide a baseline for risk-based decisions on cleanup and treatment levels. A Sitewide soil nonradioactive analyte background determination was conducted to develop Site background compositions (DOE-RL 1995). Samples representing vadose zone units were taken from both outcrop and limited borehole samples. Sample locations are shown in Figure C-1. Background levels for the list of analytes are listed in Table C-1. Analytical results for specific organic components were all below background, but some values for total organic carbon are given. Site background levels for radionuclides from samples collected in the same location are given in DOE/RL-96-12, Rev. 0 (DOE-RL 1996); these results are shown in Table C-2.

Table C-1. Sitewide Soil Background Threshold Levels Calculated from the Systematic Random Data Set Using Lognormal Distribution Results.^a
(Analyte concentrations are in units of mg/kg) (2 sheets)

Analyte	50%	80%	80% UCL	90%	90% UCL	95% LCL	95%	95% UCL
Aluminum	7600	10100	11000	11800	13000	12000	13300	15100
Antimony	—	—	—	—	—	—	—	—
Arsenic	3.55	5.28	5.89	6.47	7.38	6.61	7.65	9.06
Barium	88	115	124	132	144	134	148	165
Beryllium	1.09	1.35	1.44	1.51	1.62	1.52	1.65	1.80
Cadmium	—	—	—	—	—	—	—	—
Calcium	9450	14000	15700	17200	19700	17600	20400	24100
Chromium	9.57	14.8	16.7	18.5	21.4	18.9	22.3	26.8
Cobalt	11.2	14.0	14.9	15.7	16.9	15.9	17.3	19.2
Copper	14.4	19.0	20.6	22.0	24.1	22.3	24.7	27.9
Iron	23600	29200	31000	32600	35000	33000	35600	39000
Lead	5.45	8.24	9.36	10.2	11.7	10.4	12.2	14.5
Lithium	28.4	31.7	32.9	33.5	35.0	33.4	35.1	37.2
Magnesium	4980	6260	6680	7060	7620	7140	7780	8580
Mercury	2.3E-02	0.13	0.22	0.33	0.60	0.36	0.70	0.15
Molybdenum	—	—	—	—	—	—	—	—
Nickel	12.2	16.4	17.8	19.1	21.0	19.4	21.6	24.5

Table C-1. Sitewide Soil Background Threshold Levels Calculated from the Systematic Random Data Set Using Lognormal Distribution Results.^a
(Analyte concentrations are in units of mg/kg) (2 sheets)

Analyte	50%	80%	80% UCL	90%	90% UCL	95% LCL	95%	95% UCL
Potassium	1210	1760	1960	2150	2440	2190	2520	2960
Selenium	—	—	—	—	—	—	—	—
Silicon	15.40	36.8	37.5	44.0	55.6	—	59.0	—
Silver	5.4E-02	0.30	0.49	0.73	1.33	0.81	1.52	3.16
Sodium	231	475	581	690	878	716	937	1274
Thallium	—	—	—	—	—	—	—	—
Titanium	1460	2110	2380	2570	2950	2580	3000	3600
Vanadium	54.4	73.0	79.3	85.1	93.9	86.4	96.4	110
Zinc	51.1	61.7	64.9	67.8	72.1	68.5	73.3	79.3
Zirconium	20.6	31.8	36.4	39.8	46.8	40.0	47.8	58.8
Alkalinity	1100	3960	5680	7710	11800	8240	13300	23000
Ammonia	9.7E-01	4.28	6.48	9.23	15.1	10.0	17.3	32.5
Chloride	6.59	39.6	65.5	100	182	109	214	460
Fluoride	8.0E-01	1.83	2.31	2.81	3.70	2.93	3.98	5.7
Nitrate	3.58	20.9	34.2	52.0	93.4	56.9	110	232
Nitrite	—	—	—	—	—	—	—	—
O-Phosphate	2.1E-03	1.0E-01	3.1E-01	7.9E-01	2.87	0.96	4.08	21.5
Sulfate	10.4	81.4	145	237	469	263	566	1360

^aDOE-RL, 1995, *Hanford Site Background: Part 1, Soil Background for Nonradioactive Analytes*, DOE/RL-92-24, Rev. 3, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

— = Not enough data above the reporting limit to provide for a distribution fit.
LCL = One-sided lower confidence limit based on 95% coverage.
UCL = One-sided upper confidence limit based on 95% coverage.

Table C-2. Selected Values for the Sitewide Background Data Set.^a
(Percentiles and UCLs are based on the lognormal distribution) (pCi/g)

Analyte	Minimum	Maximum	Arithmetic mean	Standard deviation	50th percentile	90th percentile	95th percentile LCL	95th percentile	95th percentile UCL
⁴⁰ K	9.29	19.7	13.1	2.71	12.8	16.6	16.4	17.9	20.0
⁶⁰ C ^b	-0.0111	0.0387	0.00132	0.00591	0.00131	0.00842	0.00887	0.0104	0.0122
⁹⁰ Sr	0.00661	0.366	0.0806	0.0688	0.0554	0.178	0.177	0.247	0.364
¹³⁷ Cs	-0.00156	1.64	0.417	0.338	0.281	1.05	1.15	1.51	2.04
¹⁵⁴ Eu ^b	-0.0732	0.0790	0.000826	0.0250	0.000516	0.0334	0.0345	0.0427	0.0522
¹⁵⁵ Eu ^b	-0.0187	0.0984	0.0234	0.0184	0.0188	0.0539	0.0559	0.0723	0.0970
²²⁶ Ra	0.298	1.16	0.561	0.202	0.53	0.815	0.797	0.928	1.12
²³² Th	0.468	1.58	0.945	0.260	0.909	1.32	1.29	1.47	1.72
²³⁴ U	0.399	1.51	0.793	0.233	0.762	1.10	1.08	1.23	1.44
²³⁵ U ^c	0.00462	0.386	0.0515	0.0373	0.0327	0.109	0.101	0.153	0.252
²³⁸ U	0.354	1.21	0.763	0.216	0.733	1.06	1.04	1.18	1.39
²³⁸ Pu ^b	-0.000489	0.0193	0.00158	0.00332	0.000547	0.00378	0.00364	0.00648	0.0128
^{239/240} Pu ^b	-0.0050	0.0331	0.00935	0.00782	0.00661	0.0248	0.0268	0.0366	0.0521
Grossβ	13.6	25	19.78	2.40	19.45	22.96	22.63	24.07	25.88

^aDOE-RI, 1996, *Hanford Site Background: Part 2, Soil Background for Radionuclides*, DOE/RI-96-12, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

^bMajority of the data are below detection; included here for completeness.

^cUranium-235 statistics were computed using 47 samples, 17 above and 30 below detection limits. Two data items were suspended because they showed negative values.

LCL = One-sided lower confidence limit based on 95% coverage.

UCL = One-sided upper confidence limit based on 95% coverage.

C3.0 CHEMICAL PROCESSES CONTROLLING CONTAMINANT TRANSPORT IN SEDIMENT

This section considers the sediment-water chemical mechanisms that control the dissolved concentration and relative mobility of contaminants. It also covers the significant parameters and properties required to make quantitative estimates of contaminant transport control based on these mechanisms. The primary mechanisms considered are sorption and solubility-precipitation (Sections C3.1 and C3.2). Other potential mechanisms also are discussed, including particulate (including colloids) and complexant formation and ion exchange (Section C3.3). Impacts of

particulate and complexant formation are least understood for Hanford formation sediments, for many modeling purposes, these are considered secondary mechanisms.

C3.1 SORPTION AND SOLUBILITY PROCESSES

The dominant mechanisms generally used to estimate and model transport are solubility-precipitation and sorption. Sorption is a composite of several mechanisms and measures of total distribution of a contaminant between the liquid and solid phases. The sorption mechanism is used to derive a retardation factor for estimated differences between contaminant and water flow velocities.

Sorption is a generic term describing the ratio (partitioning) of the amount of a contaminant associated with a gram of solid phase (mineral) divided by the amount in solution per milliliter. Consequently, sorption is expressed in milliliters per gram, and often is expressed as K_d .

The K_d is not a true thermodynamic ion exchange constant because many mechanisms may occur together in a natural system. These mechanisms include electrostatic-type sorption on mineral surfaces, diffusion and precipitation in mineral structures, and chemical precipitation. The sorption process is generally regarded as the most important retardation process for contaminant mobility in the vadose zone. Sorption has been investigated since the early 1950's as the basis for crib disposal capacity and trench field capacity (Routson 1973). Considerable K_d data on a number of specific solution and solid systems have been determined over the years and are compiled in reviews such as Ames and Rai (1978), Delegard and Barney (1983), Serne and Wood (1990), and Kaplan et al. (1995).

The K_d is related to contaminant retardation factors in porous media by functions such as

$$R_d = 1 + (\rho_b/\phi_e)K_d$$

where ρ_b is the porous media bulk density and ϕ_e is the effective porosity at saturation or the moisture content in unsaturated media. K_d values generally apply to specific systems and are affected by factors such as competing ions, ionic strength of the solution, pH of the solution, mineralogy present in the sediments, presence of complexants, and redox conditions of the system. Most measurements were obtained in relatively simple systems with only two or three competing cations and relatively low ionic strength. Kaplan et al. (1995) summarized the major sorption mechanisms and compiled a range of K_d values for a number of contaminants under several conditions. This compilation is given in Tables C-6 through C-6 with supplementary values for some of the more mobile, long-lived radionuclides (iodine, neptunium, selenium, technetium, and uranium) from Kaplan and Serne (1995) given in Tables C-7 through C-10.

Table C-3. Reported K_d Values for Hanford Site Sediments in Neutral-to-High pH, Low Salt (Ionic Strength <0.01M), Low Organic Oxid Solutions (Version 7.0).^a
(2 sheets)

Radionuclide	Low K_d	High K_d	Reference ^a /rationale
Ac	67	1330	Am and cm analog, estimate
Am	67	>1200	ref. 8: 67 to >1200 mL/g ref. 14: 125 to >833 mL/g
C	0	4	ref. 1 and 7: wide range of K_d depending on type of organic or inorganic carbon compound, estimate
Ce	100	>2000	ref. 3: pH 6 to 12, 100 to >2000 mL/g good adsorber, insoluble
Cm	106	1330	ref. 14: 106 to 1330 mL/g
Co	1200	12,500	ref. 2: Na sys, 1290 to 2120 mL/g ref. 2: Ca sys., 2000 to 3870 mL/g ref. 9: 11,600 to 12,500 much lower K_d values exist when cobalt is organically complexed
Cs	540	3180	ref. 2: Na sys., 1410 to 1590 mL/g ref. 9: 540 to 3180 mL/g
Eu	100	228	ref. 1 and 7: Good adsorber, insoluble, estimate
I	0.04	18	ref. 9: 0.7 to 1.4 mL/g ref. 10: 0.04 to 18 mL/g
Nb	50	100	ref. 12: 50 to 100 mL/g, anionic species at pH>8
Ni	50	2350	ref. 9: 440 to 2350 mL/g ref. 12: 50 to 340 mL/g neutral and (-) charged species at high pH
Np (V)	2.4	29.1	ref. 8: Ca sys., 2.4 mL/g ref. 8: Na sys., 3.1 mL/g ref. 9: 13.5 to 29.1 mL/g
Pa	10	1000	ref. 1, 7, 11: insoluble precipitates, estimate
Pb	13,000	79,000	ref. 4: pH 6 and no competing ions, 13,000 to 79,000 mL/g
Pu (V, VI)	80	>1980	ref. 3: pH 4 to 12, 80 to > 1980 mL/g
Ra	24	100	ref. 1 and 7: estimate

Table C-3. Reported K_d Values for Hanford Site Sediments in Neutral-to-High pH, Low Salt (Ionic Strength <0.01M), Low Organic Oxid Solutions (Version 7.0).^a
(2 sheets)

Radionuclide	Low K_d	High K_d	Reference ^a /rationale
Ru	27	274	ref. 7: estimate
Se	0	0.78	Ref. 9: -3.44 to 0.78 mL/g anion
Sn	100	230	ref. 6: estimate
Sr	5	173	ref. 2: Na sys., 173 mL/g, 49 to 50 mL/g ref. 2: Ca sys., 8 to 13 mL/g, 5 to 19 mL/g ref. 3: 5 to 120 mL/g ref. 5: 40 ppm Ca sys., 10 mL/g ref. 9: 19.1 to 21.5 mL/g ref. 13: Na sys., pH 7 to 11, 14.9 to 25.1 mL/g
Te(VII)	0	1.3	ref 8: 0 to <1 mL/g ref. 9: -0.1 to 0.4 mL/g ref. 10: -0.9 to 1.3 mL/g
Th	40	100	ref. 1 and 7: estimate ^b
U (VI)	0.08	79.3	Ref. 9: 1.7 to 79.3 mL/g Unsaturated sys., 0.49 to 2.81 mL/g Saturated sys., 0.08 to 0.62 mL/g high pH sys. may form anionic complexes
Zr	90	>2000	ref. 3: pH 6 to 12, 90 to >2000 mL/g

^aKaplan, D.I. and R.J. Serne, 1995, distribution Coefficient Values Describing Iodine, Neptunium, Selenium, Technetium, and Uranium sorption to Hanford Sediments, PNL-10379, Pacific Northwest Laboratory, Richland, Washington.

^bReferences:

1 = Serne and Wood 1990
3 = Rhodes 1957
5 = Rhodes 1956
7 = Streng and Peterson 1989
9 = Serne et al. 1993
11 = Seaborg 1994
13 = Nelson 1959

2 = Routson et al. 1978
4 = Rhodes et al. 1992
6 = Lindemeier et al. 1994
8 = Routson et al. 1976
10 = Gee and Campbell 1980
12 = Serne and Relyea 1983
14 = Sheppard et al. 1976.

^cAll estimated K_d values are conservative, i.e., low k^d values.

Table C-4. Reported K_d Values for Hanford Site Sediments in Neutral-to-High pH, Low salt (Ionic Strength $<0.01M$), Low Organic, Anoxic Solutions.^{a, b}

Radionuclide	Low K_d	High K_d	Reference ^b /Rationale
Np (IV)	200	1000	ref. 1: estimate ^c
Pa (IV)	200	1000	ref. 2: estimate
Pu (III, IV)	200	1000	ref. 2: estimate
Tc (IV)	200	1000	ref. 1: estimate
U (IV)	100	1000	ref. 1: estimate

^aKaplan, D.I. and R.J. Serne, 1995, distribution Coefficient Values Describing Iodine, Neptunium, Selenium, Technetium, and Uranium sorption to Hanford Sediments, PNL-10379, Pacific Northwest Laboratory, Richland, Washington.

^bIf radionuclide is not listed, its K_d is the same as is listed in Table C-3 (Version 7.0).

^cReferences: 1 = Strenge and Peterson 1989 2 = Seaborg 1994.

^dAll estimated K_d values are conservative, i.e., low K_d values.

Table C-5. Reported K_d Values for Hanford Site Sediments in Neutral-to-High pH, High Salt (Ionic Strength $\geq 0.01M$), Low Organic, Oxidic solutions (Version 7.0).^a
(2 sheets)

Radionuclide	Low K_d	High K_d	Reference ^b /rationale
Ac	280	>1200	ref. 1: analog to Am
Am	280	>1200	ref. 4: Ca sys., >1200 mL/g. Na sys.; 280 mL/g
C	0	4	ref. 1: HCO_3^- or CO_3^{2-} , estimate
Ce	10	100	ref. 1: strong adsorber, insoluble, estimate
Cm	280	>1200	ref. 1: analog to Am
Co	222	4760	ref. 2: Na sys., 1060 to 4760 mL/g ref 2: Ca sys., 222 to 640 mL/g forms complexes especially with organics
Cs	64	1360	ref. 2: Na sys., 64 to 1170 mL/g ref. 2: Ca sys., 790 to 1360 mL/g no complexes, good adsorber
Eu	10	500	ref. 1: strong adsorber insoluble, estimate
I	0	0.5	ref. 1: anion, estimate ^c
Nb	5	25	ref. 6: estimate

Table C-5. Reported K_d Values for Hanford Site Sediments in Neutral-to-High pH, High Salt (Ionic Strength $\geq 0.01M$), Low Organic, Oxidic solutions (Version 7.0).^a
(2 sheets)

Radionuclide	Low K_d	High K_d	Reference ^b /rationale
Ni	3	40	ref. 1: moderate complex former, estimate
Np (V)	0.4	4	ref. 4: 0.4 to 4 mL/g
Pa	5	500	ref. 5: forms insoluble precipitates, estimate
Pb	20	1000	ref. 1: good adsorber, insoluble, estimate
Pu (V, VI)	10	>98	ref. 3: >98 mL/g ref. 1: lower K_d value is a conservative (low) estimate
Ra	10	50	ref. 1: divalent cation, estimate
Ru	0	10	may form RuO_4^{2-} and anionic complexes with $Ru-NO_2-NO_3$, estimate
Se	0	4	ref. 1: anion, estimate
Sn	10	1000	insoluble, estimate
Sr	0.3	42	ref 2: Na sys., 1.7 to 42 mL/g ref. 2: Ca sys., 0.3 to 1.6 mL/g
Te (VII)	0	0.01	Ref. 4: 0 to 0.01 mL/g. anion
Th	40	470	ref. 7: sandy soil data, 40 to 470 mL/g, estimate
U (VI)	0	4	ref. 1: estimate, anionic and neutral carbonate ref. Complexes, estimate
Zr	20	200	ref. 1: strong adsorber, estimate

^aKaplan, D.I. and R.J. Serne, 1995, distribution Coefficient Values Describing Iodine, Neptunium, Selenium, Technetium, and Uranium sorption to Hanford Sediments, PNL-10379, Pacific Northwest Laboratory, Richland, Washington.

^bReferences: 1 = Serne and Wood 1990
3 = Rhodes 1957
5 = Seaborg 1994
7 = Sheppard et al. 1976

2 = Routson et al. 1978
4 = Routson et al. 1976
6 = Serne and Relyea 1983

^cAll estimated K_d values are conservative, i.e., low K_d value.

Table C-6. Reported K_d Values for Hanford Site Sediments in Neutral-to-High pH, High Salt (Ionic Strength $<0.01M$), Low Organic, Anoxic Solutions.^{a, b}
(Kaplan et al. 1995)

Radionuclide	Low K_d	High K_d	Reference ^c /Rationale
Np (IV)	100	1000	ref. 1: estimate ^d
Pa (IV)	100	1000	ref. 2: estimate
Pu (III, IV)	100	1000	ref. 1: estimate
Te (IV)	100	1000	ref. 1: estimate
U (IV)	100	1000	ref. 1: estimate

^aIf radionuclide is not listed, its K_d is the same as is listed in Table C-5 (Version 7.0)

^bReferences: 1 = Strenge and Peterson 1989 2 = Seaborg 1994

^cAll estimated K_d value are conservative, i.e., low K_d value.

Table C-7. K_d Values for Hanford Site Sediments in Neutral-to-High pH, Low Ionic Strength ($\leq 0.01M$), Low Organic, Oxidic Solutions (Kaplan and Serne 1995).

Radionuclide	Low K_d	High K_d	Number of Samples	Mean \pm Std Err.	Variance	Median	Best Estimate
I	0.7	15.0	9	6.5 ± 1.7	25.02	7	3
Np	2.4	21.7	4	14.9 ± 4.4	76.94	17.8	15
Se	-3.4 ^(a)	0.8	3	-1.7 ± 1.3	4.83	-2.4	0
Tc	-2.8	0.6	15	-0.3 ± 0.2	0.85	0.1	0
U	0.1	79.3	13	7.0 ± 6.0	472.3	0.6	0.6

^(a)Negative K_d values are physically impossible and represent analytical or laboratory error.

Table C-8. Estimate K_d Values for Hanford Site Sediments in Neutral-to-High pH, Low Ionic Strength ($\leq 0.01M$), Low Organic, Anoxic Solutions (Kaplan and Seren 1995)

Radionuclide	Low Estimate	High Estimate	Best Estimate	References ^(a)
I	0	15	3	1,2,3,4
Np	200	1000	200	2,5,6
Se	0	3	0	2,7,8,9,10,11
Tc	200	1000	200	2,5,12,13
U	100	1000	100	2,14,15,16

^(a)References:

1 = Serne and Wood 1990
 3 = Muramatu et al. 1990
 5 = Bondietti and Francis 1979
 7 = Rai and Zachara 1984
 9 = Frost and Driffin 1977
 11 = Benjamin and Bloom 1981
 13 = Hanke et al. 1986
 15 = Carnahan 1988

2 = Strenge and Peterson 1989
 4 = Tichnor and Cho 1990
 6 = Ames and Rai 1978
 8 = Singh 35 al. 1981
 10 = Leckie et al. 1989
 12 = Gu and Schulz 1991
 14 = Rai et al. 1990
 16 = Bruno et al. 1988.

Table C-9. K_d Values for Hanford Site Sediments in Neutral-to-High-pH, Low Ionic Strength ($\leq 1.0M > x > 0.01M$), Low Organic, Oxidic Solutions (Kaplan and Serne 1995).

Radionuclide	Low K_d	High K_d	Number of Samples	Mean \pm Std. Err.	Variance	Median	Best Estimate
I	0.4	0.7	4	0.5 ± 0.06	0.015	0.5	0.5
Np	0.3	3.8	8	2.2 ± 0.6	2.61	2.3	2
Se ^(a)	0	2					0
Tc	-3 ^(b)	0.04	3	-0.98 ± 1.0	3.07	0.03	0
U ^(a)	0	4					0

^(a)All selenium and uranium values are estimates based on Table 1.1, Serne and Wood (1990), and Strenge and Peterson (1989).

^(b)Negative K_d values are physically impossible and represent analytical or laboratory error.

Table C-10. Reported Best-Estimate K_d Values for Hanford Site Sediments in Neutral-to-High pH, High Ionic Strength ($1.0M > x > 0.01M$), Low Organic, Anoxic Solutions (Kaplan and Serne 1995).

Radionuclide	Low Estimate	High Estimate	Best Estimate	References ^(a)
I	0	15	0	1,2,3,4
Np	100	1000	100	2,5,6
Se	0	2	0	2,7,8,9,10,11
Tc	100	1000	200	2,5,12,13
U	100	1000	100	2,14,15,16

^(a)References:

1 = Serne and Wood 1990
 3 = Muramatsu et al. 1990
 5 = Bondietti and Francis 1979
 7 = Rai and Zachara 1984
 9 = Frost and Driffin 1977
 11 = Benjamin and Bloom 1981
 13 = Hanke et al. 1986
 15 = Carnahan 1988

2 = Strenge and Peterson 1989
 4 = Tichnor and Cho 1990
 6 = Ames and Rai 1978
 8 = Singh et al. 1981
 10 = Leckie et al. 1980
 12 = Gu and Schulz 1991
 14 = Rai et al. 1990
 16 = Bruno et al. 1988

The solubility mechanism can involve both acid-base-driven solubility and oxidation-reduction-controlled solubility, as well as solubility limits based on ionic strength. Under normal soil-water chemical conditions, solubility reactions are considered to be significant for only a few radionuclides, principally uranium and, perhaps, transuranic elements.

Extensive literature, ranging from multicomponent field studies to specific solute-mineral chemistry at the atomic level, is available about mineral-water interactions. Some of this literature is reviewed in compilations such as Sposito (1984) and Stumm and Morgan (1981). This literature, along with numerous studies done at the Hanford Site, form the technical basis for determining parameters and properties of vadose zone materials that control contaminant transport. Over the last 40 years, a number of reviews of the Hanford site literature dealing with soil and sediment chemistry have been conducted. These reviews have focused primarily on sorption and related processes that influence contaminant retention capacity of sediments and retardation factors. These include Benson (1960); Routson (1973); Ames, Rai, and Serne (1976); Ames and Rai (1978); Serne and Wood (1990); and Serne et al. (1998). These reviews generally include most of the literature on sediment-waste interactions that contain data on ionic strength, K_d s and competing cations, cation exchange capacity, soil pH, and related sorption properties. In addition, recent analyses of contaminant transport factor needs provide a basis for determining the limitations of available data. These analyses were conducted as part of performance assessments of disposal systems (Serne et al. 1993, Kaplan et al. 1995) and groundwater quality assessments at specific tank farms (Johnson and Chou 1998, Hodges 1998, and Narbutowski 1998).

C3.2 SUMMARY OF PARAMETERS USED TO QUANTIFY

SORPTION-SOLUBILITY REACTIONS

The Sitewide background chemical data for soils already considered provides a regional baseline for evaluating contamination levels. Local background levels for specific tank farm and crib systems may need to be established to evaluate selected trace elements, radionuclides, and ion ratios of interest for specific cases. These local background values, possibly obtained from spectral gamma logging or well sample analysis become the baseline for assessing future contaminant migration.

Solubility and sorption behavior are controlled by a number of parameters, a fundamental one is the pH of solutions in contact with minerals. Background pH values of groundwater provide a measure of acidity in saturated systems and are available from annual groundwater monitoring reports (e.g., Hartman and Dresel 1997) and other specific studies. In general, the natural mineral-water buffering capacity of Hanford Site groundwater systems results in pH ranges of about 7.5 to 8.5. Johnson and Chou (1998) report groundwater pH ranges of 7.9 to 8.3 in wells in the S-SX farm complex, while Hodges (1998) reports values between 7.1 and 8.5 in the T-TX-TY farm area. In a well near the Fast Flux Test Facility (FFTF) that represents an area with a low probability of process contamination, Serne et al. (1995) report a range of pH values from 7.8 to 8.5 from samples collected over 5 years. Another type of pH measurement, more representative of unsaturated vadose zone conditions, is soil pH. These measurements are less frequently reported and more difficult to obtain. In laboratory measurements of extracts from soil-water systems that range from 1 g of soil to 30 ml of water to 1 to 1 that were allowed to react for various times, pH ranged from 7.7 to 8.2 (Serne et al. 1998) and in recent samples from the SX borehole extension, values of 8.5 to 8.8 were obtained with 1-to-1 extracts.

The overall capacity of soils and sediments to sorb ions, their selectivity for specific ions, and the reversibility of the sorption process are important in assessing the long-term ability of sediments to retain contaminants or retard mobility. The general sorption capacity of unit mass of soil usually is expressed by the cation exchange capacity (CEC). Typically, soils and sediments with a high clay and silt content have a higher CEC than sediments with a higher coarse-grained fraction. The CEC measures the amount of contaminants that may be sorbed from leaked or discharged waste for a given mass of sediments before breakthrough occurs. Typical CEC values for Hanford Site soils are 5 meq/100 g to 8 meq/100 g (Ames and Rai 1978 and Serne et al. 1993). The CEC does not provide information on cation selectivity. Clay minerals and related fine-grained minerals have several different kinds of sorption sites related to their crystal structures that are more reactive to certain cations than others. Several of these types of sites and associated sorption mechanisms are discussed by Kaplan et al. (1995).

Selectivity also depends on the chemical state of the carrier solution, which is governed by the presence or absence of complexants, ionic strength of solutions, chemical speciation, and redox conditions. For given sediment mineral assemblage and waste solution chemical composition, selectivity can result in contaminant separation and modification to K_d parameters depending on local site conditions. A final sorption-related parameter is cation exchange reversibility, which measures the ability of sediments to retain sorbed ions or resist elution following subsequent contact with water or additional waste solutions. In some ion exchange systems, such as those involving primarily electrostatic surface sorption, reversibility appears to

occur fairly readily. For example, soils at the Hanford site generally are based with calcium, but waste with high sodium concentrations, such as tank waste appears to replace the calcium sites with sodium. This results in high calcium sodium ratios at the leading edge of waste plumes, as was suggested for the S-SX farm (Johnson and Chou 1998). In other cases, cesium sorbed on specific structural sites in mica-illite-type clays appears to be strongly bonded and difficult to remove (Kaplan et al. 1995). Subsequent elution may be more related to mineral solubility control than ion exchange. The degree of reversibility that occurs in sediment-water reactions leads to a variable amount of hysteresis when considering forward and reverse K_d models. The degree of reversibility may become important in multiple-contaminant release events at the same site.

Electrical conductivity and Eh are used to estimate dissolved solids and oxidation-reduction conditions, respectively, in groundwater. Measurements of these parameters in uncontaminated groundwater provide a baseline of pore water chemistry in saturated situations that can be used for comparison with unsaturated condition. According to Johnson (1993), specific conductance of natural groundwater at the Hanford Site is about 200 to 350 $\mu\text{S}/\text{cm}$, while the conductance of Columbia River water used as a makeup water is about 140 $\mu\text{S}/\text{cm}$. For comparison, specific conductance of contaminated groundwater such as is found under the T-TX-TY farms can be above 2000 $\mu\text{S}/\text{cm}$ (Hodges 1998). Natural groundwater may not be at saturation with respect to all available minerals in sediments, which suggests that the specific conductance may represent a lower limit. In the vadose zone, with higher ratio of mineral surface to water volume, conductivities in water that only partially fills pore volumes will probably be higher than in the saturated groundwater zone because of greater chance for chemical saturation to occur.

Eh of groundwater or solution extracts from soil-water laboratory tests measure the oxidation reduction potential to the soil-water system and can control some types of dissolution-precipitation reactions by influencing chemical speciation. As a possible baseling estimate for uncontaminated groundwater, measurements over 5 years from well 6-S3-25 near the FFTF are in the range of 280 to 380 mv (Kaplan et al. 1995). Values of extracts from soil-water systems range from 370 to about 380 mv for 4 different soils of the Hanford formation (Serne et al. 1993). These Eh values, taken with the pH values of about 8, indicate that these waters are moderately oxidizing. The vadose zone conditions would be expected to be even more oxidizing because pore volumes also are partially filled with air. Locally, however, reducing systems may occur, even in the vadose zone, because minerals or other substances acting as reducing agents are present. These might consist of reduced iron-bearing minerals, such as magnetite or pyrite, or high organic components. These minerals most likely would occur in the fine-grained fractions, such as silts and clays.

C3.3 COMPLEXANTS, COLLOIDS, AND PARTICULATES

Most contaminant transport conceptual models used at the Hanford Site assume a two-phase system with an immobile solid phase and mobile liquid phase with dissolved components. The formation or occurrence of complexants, colloids, and particulates can potentially modify this concept, but the quantitative impact and the contribution of these mobile solid materials on overall

transport mechanisms is controversial and not well understood. Complexants may result in a greater concentration of contaminants in solution than would be expected based only on solubility or sorption mechanisms. Some examples are carbonate complexes of uranium organic complexants of alkaline earths (e.g., strontium). Thus organic components in leaked or discharged waste solutions may result in complexant formation, leading to a greater contaminant distribution volume or depth in the vadose zone than otherwise would be expected. As a limited indication of total organic carbon (TOC) observed in groundwater, Serne et al. (1993) indicate a range of 0.03 to 1.7 mg/L in well 6-S3-25 near the FFTF, while Hodges (1998) observed values ranging from <0.2 to 1.5 mg/L in wells near the T-TX-TY farm. Extracts from soils may be an order of magnitude higher; Serne et al. (1993) obtained values ranging from 12.7 to 17.2 mg/L from 4 soil samples. The higher TOC in these samples may have been influenced by vegetation components because of their near-surface location. As an example of possible background data for uncontaminated Hanford formation water, chemical data from well 6-S3-25 are given in Table C-11.

Table C-11. Chemical Composition (mg/L) of Groundwater from Well 6-S3-25 (Serne et al. 1993).

Constituents	Sample used (4/90)	Range in composition (1985-1990)
pH	8.14	7.82 - 8.47
Eh(mv)	309	283-385
Al	<0.03	<0.03 - 0.064
B	0.1	0.02 - 0.10
Ba	0.08	0.04 - 0.08
Ca	48.8	48.8 - 58.8
Cd	<0.004	<0.004
Cr	<0.020	<0.02 - 0.034
Cu	<0.004	<0.004
Fe	<0.005	<0.005 - 0.008
K	9.9	4.9 - 9.9
Li	<0.004	<0.004
Mg	14.6	13.2 - 14.6
Mn	<0.002	<0.002 - 0.13
Na	32.1	23.8 - 32.1

Table C-11. Chemical Composition (mg/L) of Groundwater from Well 6-S3-25 (Serne et al. 1993).

Constituents	Sample used (4/90)	Range in composition (1985-1990)
P	<0.1	<0.1
Pb	<0.06	<0.06
Si	16.4	14.6 - 16.4
Sr	0.25	0.23 - 0.25
Zn	<0.02	<0.02 - 0.08
F	0.5	<0.5 - 0.7
Cl ⁻	27	21 - 27
NO ₂ ⁻	<0.3	<0.3
NO ₃ ⁻	<0.5	<0.5
PO ₄ ³⁻	<0.4	<3
SO ₄ ²⁻	75	63 - 92
T-Alk (as CO ₃ ²⁻)	67.5	67.5 - 92.4
TOC	1	0.3 - 1.7
Cations (meq/L)	5.29	4.9 - 5.4
Anions (meq/L)	4.60	4.6 - 6.1

Kaplan et al. (1995) briefly describes possible colloid and particulate contributions. Vadose zone colloids could originate from three mechanisms: dispersion of subsurface sediments, dissolution of particulate cements allowing for particulate mobility, and precipitation of groundwater constituents. According to Kaplan et al. (1995), a likely source for vadose zone colloids at the Hanford Site may be precipitation because these colloids are generally smaller than 100 nm, while those from detrital sediments tend to be larger than 200 nm. Clay minerals have a crystalline atomic structure and are generally considered as the less than 2 μm fraction in soils. They are linked to the colloid issue because their formation involves a colloidal process (van Olphen 1977). Sample preparation for groundwater often includes filtering through a 0.45 μm filter. If groundwater analyses indicate significant differences between filtered and unfiltered samples, the presence of particulates may be suspected and further analysis warranted. Determining if colloids are a significant contributor to contaminant transport is difficult, as pointed out by Kaplan et al. (1995).

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APPENDIX D

RESUMES

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APPENDIX D

RESUMES

T. E. Jones. Tom Jones earned a Ph.D. in inorganic/analytical chemistry from Washington State University, did postdoctoral research at Wayne State University, and was on the faculty at the University of New Mexico. His research focused on developing a fundamental understanding of the kinetics and thermodynamics of electron-transfer and metal ion complexation reactions in aqueous and non-aqueous solvents. Since arriving at the Hanford Site in 1980, Dr. Jones has provided technical support for hydrogeological characterization of the basalt flows underlying the Hanford Site, developed analytical laboratory management systems to support waste-site characterization under the *Resource Conservation and Recovery Act of 1976* and the *Comprehensive Environmental Response, Compensation, and Recovery Act of 1980*, developed and managed a tank waste analytical characterization program, prepared chemical and radionuclide inventory estimates for some two dozen high-level waste tanks, and provided technical and regulatory support to the U.S. Department of Energy's Tank Waste Remediation System (TWRS) Privatization Program. His support to the TWRS Vadose Zone Program has focused on developing relationships between tank waste chemistry and vadose zone contamination.

R. Khaleel. Dr. Khaleel holds a Ph.D. in Soil and Water Engineering from Texas A&M University and has over 25 years experience in groundwater hydrology and numerical simulations of subsurface flow and transport. Dr. Khaleel was a key contributor to the Hanford Site solid waste performance assessments, particularly in developing conceptual models, directing the modeling, and preparing the documentation.

D. A. Myers. David Myers earned a MS in geology and hydrology from the University of Idaho. He is a registered professional geologist in Idaho and Oregon. His work has focused on water resources, as well as environmental monitoring and remediation of groundwater contamination. Since arriving at the Hanford Site in 1974, Mr. Myers has provided technical support for the Site-Wide Groundwater Monitoring Program, as well as early development of the *Resource Conservation and Recovery Act of 1976* monitoring program for the Low-Level Waste Burial Grounds. He served as a senior hydrogeologist within the environmental restoration program, actively participating in the design and implementation of groundwater remediation projects. He supports the TWRS Vadose Zone Program as a technical coordinator, ensuring that multiple aspects of this complex problem are integrated and coordinated.

J. W. Shade. Dr. Shade has degrees in geology and chemistry from Miami University (Ohio) and a Ph.D. in geochemistry from Pennsylvania State University. He has over 30 years experience in geochemistry and material science, with over 20 years of that addressing nuclear and hazardous waste environmental problems. His research interests include waste-form development, leach testing methodology development, waste-form durability studies, water-rock interactions, waste package systems design, in situ vitrification, and cement and glass chemistry. He provided technical oversight, coordination, and integration for components of the Hanford Site grout technology program.

M. I. Wood. Marc Wood received a B.S. in geology from the University of North Carolina in 1973 and a Ph.D. in geology from Brown University in 1980. Dr. Wood is currently responsible for maintaining Performance Assessment analyses completed to support the disposal authorization for solid low-level waste in the active 200 Area Low-Level Burial Grounds (LLBG). Two analyses have been completed that evaluate potential long-term radionuclide releases into the surrounding environment from the 200 West and 200 East Area LLBG. He also has directed numerous projects to quantify the geochemical properties of radionuclides in the Hanford Site's geohydrologic environment.

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